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AN ELEMENTARY COURSE OF PHYSICS

EDITED BY

REV. J. C. P. ALDOUS, M.A.

LATE FELLOW OF JESUS COLLEGE, CAMBRIDGE; FORMERLY CHIEF INSTRUCTOR H.M.S. *BRITANNIA*

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DEDICATED

BY SPECIAL PERMISSION

TO HER MOST GRACIOUS MAJESTY

QUEEN VICTORIA

IN WHOSE GLORIOUS REIGN

SCIENCE HAS WON

ITS TRIUMPHS

PREFACE

This Manual of Physics took its rise from a desire to relieve the subject of the foreign element of unreality, and to give a modern and practical course of Natural Philosophy in a compendious form.

The illustrations are almost all new, and the editor, owing to a temporary lull in the demand for the beautiful art of wood-engraving, was able to secure the services of one of its best exponents, Mr. Octave L. Lacour, who has executed 292 blocks for the work. They often represent actual lecture-room apparatus, which those who have attended lectures will recognise; these pictures may supply the place of apparatus to those who are obliged to study alone. The illustration of the book would have been impossible but for the continuous advice and help of Mr. J. H. Spanton, who always placed his artistic talent at the disposal of his friends in H.M.S. *Britannia*.

It was the original intention of the editor to secure the revision of the whole book by one scientific man of eminence; but, owing to the kindness of friends, he was led to the preferable plan of securing the advice in each part of

one who had made the subject a special study. For this immense advantage he is indebted to the extreme kindness of the late Lord Kelvin, of Lord Rayleigh, Professor J. A Ewing, Captain Wilson Barker, and others.

Those parts which have not received this advantage will no doubt find many generous critics, whose comments will be eagerly welcomed; the book owes much to them.

Such a book must, perforce, be a compilation, and the Editor can only express generally his indebtedness to all whose researches are referred to. In *Nature*, in Lupton's Tables, in Molesworth's *Pocket-Book*, the progress of Physics, the results of experiments, and the practical application of the laws of Nature are recorded; the compiler can only hope to secure accuracy by availing himself of such information.

A complete Index renders the usual Table of Contents and List of Illustrations unnecessary.

MECHANICS—PROPERTIES OF MATTER
—HYDROSTATICS—HEAT

BY

REV. J. C. P. ALDOUS, M.A.

LATE FELLOW OF JESUS COLLEGE, CAMBRIDGE; FORMERLY CHIEF INSTRUCTOR
H.M.S. *BRITANNIA*

WAVE MOTION—SOUND—LIGHT

BY

W. D. EGGAR, M.A.

ASSISTANT MASTER, ETON COLLEGE

MAGNETISM—ELECTRICITY

BY

F. R. BARRELL, M.A., B.Sc.

PROFESSOR OF MATHEMATICS, UNIVERSITY COLLEGE, BRISTOL
FORMERLY INSTRUCTOR IN NATURAL SCIENCE IN H.M.S. *BRITANNIA*

PREFATORY NOTE

The Editor, as Author of this portion, wishes to provide his readers with a ground-work of theoretical knowledge which may enable them to understand and use the simple processes of the kinetic method, to express themselves with accuracy when necessary, and to deal with simple mechanical problems. At the same time he would make it clear how far the ordinary language of practical men may be used without inaccuracy in practical matters so long as the fundamental ideas of mass, inertia, force, and motion are thoroughly understood.

He wishes to acknowledge how much he owes to the criticisms of his fellow-authors, especially of Professor F. R. Barrell, and he cannot sufficiently express his obligation to Mr. R. T. Glazebrook for the use of his lucid and practical text-books, and for his introduction to so many helpful friends.

MECHANICS

CHAPTER I

Motion

Newton's Observations—Newton's First Law—Kinematics—Kinetics—Motion —Rest—Absolute Rest—Relative Motion—Speed or Rate of Motion—Standards of Length—Units of Length—Standard of Time—Unit of Time —Velocity of a Point—Variable Velocity—Uniform Velocity—Acceleration —Uniform Acceleration—Acceleration in one Straight Line—Space described by a Moving Point—$s = vt : s = \frac{1}{2}at^2 : v^2 = 2as : v^2 - u^2 = 2as$—Velocity acquired by a Moving Point—Acceleration of Initial Velocity—Summary —Parallelogram of Velocities—Resolution of Velocities—Parallelogram of Accelerations—Trajectory—Motion in a Circle—Motion of a Body.

It seems to be a well authenticated story that Sir Isaac Newton was obliged by the plague in 1665 to leave Cambridge and retire to Woolsthorpe, and that there, whilst in the orchard, a falling apple attracted his eye and mind. The fall of the apple led to a train of thought which he followed until one of the riddles of the universe was solved. Even if the story be not exactly true, the principle which underlies it is a true one—that correct observation of what actually occurs is the only true guide to knowledge. The fact which then presented itself to Newton's observation may be said to be the first and most obvious fact of human experience—that bodies fall towards the earth. A child's first fall teaches the fact, but to be the first to draw the correct inferences from this well-known fact required a Newton's mind.

Some of these inferences may be shortly stated. First, the apple will not fall unless it be made to do so. The stalk

becomes weak, it is true, but this does not move the apple; some cause there must be to account for its first movement. Secondly, the direction of motion must afford a clue to the cause of motion —the apple falls to the earth, it does not rise from it; and a cause must be sought for in the direction of the centre of the earth. Thirdly, when once the apple has left the tree and begun to fall, its speed increases on the way down, and it is reasonable to conclude that the same cause which makes it begin to move increases its rate of falling as it goes.

Newton in fact took up the study of motion where G. Galilei had left it, and as a result of his observations formulated the three laws which are known by his name.

Newton's First Law of Motion.—*Every body continues in its state of rest or of uniform motion in a straight line except in so far as it is compelled by external force to change that state.*

Expressions are used in the first law of motion which should be understood before further illustrations of the law itself can be profitably studied. The terms used here—motion, rest, uniform motion, body, force—need interpretation.

Kinematics (κίνημα, *kinema*, a movement) is the name given

to the study of the motion or rest of a point or of a body, without any reference to the matter of which the body is composed or to the causes of motion.

Kinetics (*κινητικά*, that which makes movement) is the study of moving bodies, taking into consideration the amount of matter in them and the causes which affect their motion.

Kinematics or the Science of Motion

Motion is change of position.

Rest is absence of motion.

Absolute Rest is not to be found in nature. The earth is spinning round in its daily and its yearly motion, the solar system is moving in space; on this moving earth we may be travelling in an express train. Yet we may say truly that a foot warmer remains 'at rest' on the floor; it is at rest relatively to the carriage in which we are travelling. The falling apple was at rest on the tree until the stem was no longer able to resist the downward pull of the earth's attraction. Amid all the complexity of movement in our surroundings no point can be said to be absolutely at rest. Motion and rest must be considered relatively to surrounding objects.

Motion, in its most general sense, must be approached through the study of the motion of a point.

Relative Motion is a change of distance from points to which the motion is referred. Motion cannot be estimated otherwise than relatively. If a ball be dropped from the roof of a railway carriage in a fast express it will fall to the floor. We say, 'it falls down.' We do not estimate the true path of the ball in space. All the points to which its motion can be referred are moving rapidly. Since we are in the carriage, we refer the motion to it and speak of the ball as moving 'down.'

Speed or **Rate of Motion** of a point is the number of units of length traversed in a unit of time.

Standards of Length.—Two standards of length are used in this book.

THE BRITISH YARD is the distance at 62° F. between the centre marks in two gold plugs let into a bronze bar kept in the Standards Department of the Board of Trade.

1 mile = 1760 yards. 1 yard = 3 feet. 1 foot = 12 inches.

THE MÈTRE is the length at 0° C. of a platinum bar kept in the Bureau des Archives, Paris. The metre was originally intended to be the ten-millionth part of a quadrant of a terrestrial meridian (see p. 100). A copy of this Standard is also kept in the Standards Department.

1 kilometre = 1000 metres. 1 metre = 100 centimetres = 1000 millimetres.

Comparison—

1 yard = ·9144 metre. 1 metre = 1·0936 yard.

Units of Length.—The CENTIMETRE (cm. or c.) and the FOOT (ft. or f.) are the units of length most frequently employed in scientific investigations. Larger or smaller units are employed in the measurement of very large or very small distances.

The comparison of quantities measured by different units is facilitated by the scales given on pp. 97, 99.

Standard of Time.—The standard of time in common use is the mean solar day.

1 day = 24 hours. 1 hour = 60 minutes. 1 minute = 60 seconds.

Unit of Time.—The SECOND (sec. or s.) is the unit of time most frequently employed in scientific investigations where moderate intervals are considered.

Velocity of a Point.—Speed or rate of motion does not take any account of the direction of motion or of the path traversed by the point. The term *Velocity* includes the idea of direction.

Velocity is a complete description of the movement of a point at a given moment; it may be changing its rate or direction of motion in any way; at that moment the point is moving with a definite speed in a definite direction, and that is its velocity.

THE VELOCITY OF A POINT is the number of units of length which it would traverse in a unit of time in the direction of its

motion at that moment if its motion were continued unchanged for the whole unit.

A velocity can be represented completely by a straight line. A straight line has magnitude, and it has direction; the magnitude representing the speed or rate of motion, and the direction being that of the motion of the point at the moment, the straight line completely represents the velocity.

If a shot be fired from a big gun, it leaves the muzzle with a definite speed, say 2600 ft. per sec. Considering its motion as the motion of a point (Fig. 2), it is moving then in a certain direction MT, so that if it continued to move at that rate or speed for a whole unit of time it would traverse a number of units of

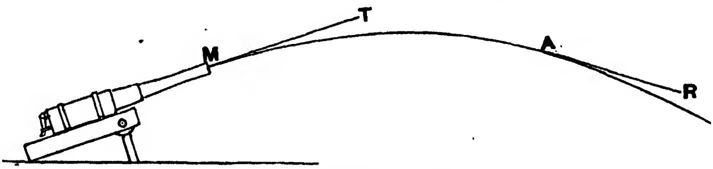


Fig. 2.—Variable velocity.

distance in that direction, represented by the length of the line MT. The line MT then represents the velocity of the shot at M.

Variable Velocity.—Referring again to Fig. 2, the shot when it has reached a point A has a different velocity from that which it had at M. It is then moving in a different direction AR, and at a different rate. AR, which has been drawn to represent the velocity at A in magnitude and direction, differs from MT, which represents the velocity at M. The velocity of the shot is continually changing in magnitude and direction during its whole flight; this is called *variable velocity.*

Uniform Velocity.—If a point move so as to describe equal distances in equal periods of time, however small, and always in the same straight line, it is said to move with *uniform velocity.*

Uniform velocity does not, so far as we are aware, exist in nature, but it is necessary to consider uniform velocity as an assistance to the study of variable velocities.

Velocity is measured by the number of feet or centimetres

traversed in a second; these are usually denoted by the shortened forms, f.s. or c.s.

Acceleration is the change of a velocity per second.

Acceleration must be distinguished from rate of increase of speed just as velocity is distinguished from speed, by the addition of the idea of direction. If the acceleration of a point be in a direction different from that of its velocity, the direction of motion is changed.

Uniform Acceleration.—If the velocity of a point is changing uniformly, whether in magnitude or direction, its changes in successive equal intervals of time, however small, being equal, the point has a *uniform acceleration.*

Variable accelerations occur in nature, in which the changes of velocity in successive intervals are not equal; these will not be treated of here.

Acceleration is described by the velocity (c.s. or f.s.) added per sec., and is shortly expressed by c.s.s. or f.s.s.

Acceleration in one Straight Line.—The simplest case of acceleration is that in which the motion takes place in a straight line. In this case the speed is changed, but not the direction of the velocity. This form of motion is seen in the case of a falling body,—the increase of the velocity is the same in each second.

If a velocity of 3 centimetres per sec. be added in each second to the velocity of 30 centimetres per sec. with which a point is moving, the point is said to have an acceleration of 3 c.s.s. (*i.e.* 3 centimetres per sec. added in each sec.). After 6 sec. the velocity of the point will be 48 c.s. (*i.e.* 48 centimetres per sec.).

If the acceleration be of a negative sign, what is called 'acceleration' is really a retardation. As an example:—If a point moving with a velocity of 20 f.s. (*i.e.* 20 ft. per sec.). have a negative acceleration of 2·5 f.s.s. (*i.e.* 2·5 ft. per sec. subtracted in each sec.), after 8 sec. the velocity of the point will be zero; it will be reduced to rest.

The product of the acceleration and the number of units of time during which it has been in operation, when added to the *initial velocity*, gives the *final velocity.* Let the *initial velocity* be

u ft. or cm. per sec., the *final velocity* v ft. or cm. per sec., and the *acceleration* a ft. or cm. per sec. added in each sec., *i.e.* a f.s.s. or c.s.s., then after a *time* t sec. $v = u + at$.

Space described by a Moving Point—(1) *Uniform motion.*—If a train move uniformly at a rate of 55 miles an hour for two hours, it will travel 110 miles. This is an example of a distance traversed with a uniform rate of motion. The distance is the product of the number of units of time during which the point has been moving, and the number of units of length it passes over in a unit of time.

To some minds, a geometrical figure gives a truer sense of magnitude than algebraical expressions convey, the eye can compare the different parts and it assists the mind in estimating their proportions. In Natural Philosophy the representation of quantities graphically has many distinct advantages, and this is especially the case when operations follow one another or some action takes place continuously. The algebraical expression represents the state of things at a certain time, the geometrical representation may show the whole operation carried on continuously. Considerable use will be made of the graphical method in this book, and as it is particularly suitable for describing motion, the subject will be treated graphically, though the algebraical expressions are given as well.

It has been observed that velocities may be represented by straight lines both in magnitude and direction. Time can also be represented graphically by a straight line containing as many units of length as there are seconds in the period of time. Let the velocity of a point moving uniformly in a straight line be denoted by the line AB (Fig. 3). At right angles to AB draw the line AC representing in magnitude the t seconds during which the point has been moving. Then the distance traversed by the point in the time will be

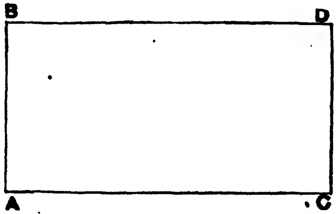


Fig. 3.—Uniform motion, $s = vt$.

represented in magnitude by the rectangle AD. The space described in t sec. by a point moving with a uniform velocity of v ft. or cm. per sec. being s ft. or cm. Then

$$s = v \cdot t.$$

(2) *Uniform acceleration, starting from rest.*—A point at rest is given a uniform acceleration of a f.s.s. (a ft. per sec. in each sec.), it is required to find the space described in t sec.

Draw a horizontal line AM (Fig. 4) to represent t sec., and number it at intervals 1, 2, 3, etc., to represent seconds, the whole line AM corresponding to t seconds, the whole time during which the movement of the point is considered. At the point

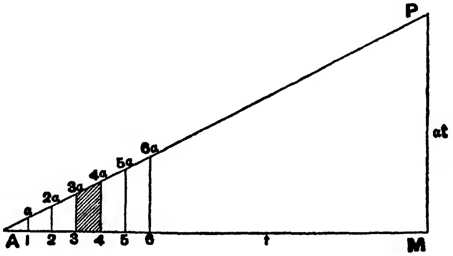


Fig. 4.—Acceleration, $s = \frac{1}{2}at^2$.

1 draw a vertical line representing in magnitude the acceleration a, and at 2, 3, 4, lines equal to $2a$, $3a$, etc.; these will represent the velocities after 2, 3, 4, etc. seconds, and at M draw PM equal to at, the velocity at the end of the t seconds; then the straight line AP will pass through the ends of the lines a, $2a$, $3a$, and complete the right-angled triangle. As in the last proposition, each of the small areas between these vertical lines is a measure of the distance which the point passes over during a second. Take any one as an example,—the space passed over in the fourth second (this one is shaded to distinguish it). At the beginning the velocity is $3a$, and if this velocity were continued for the whole sec. a distance $3a$ ft. would be traversed; at the end the velocity is $4a$, and if the point had this velocity during the whole sec. $4a$ ft. would have been traversed. Therefore during the

fourth second the point traverses a distance half-way between $3a$ and $4a$ ft., and this is measured by the shaded area.

These areas, then, represent in magnitude the distances traversed in successive seconds, and the whole triangle represents the distance described in the whole time. Its area is half the rectangle contained by AM and MP. AM $=t$ and PM $=at$, and the area of AMP $=\frac{1}{2}t \times at = \frac{1}{2}at^2$.

Hence the space passed over in t sec. by a point initially at rest and subjected to an acceleration of a f.s.s. is s feet, where

$$s=\tfrac{1}{2}at^2.$$

A point moving with uniform acceleration describes 300 ft. in five seconds from the beginning of motion. Find how many feet it will describe in eight seconds.

In the five sec. $\frac{1}{2}at^2=300$, where $t^2=25$, so that $a=24$ f.s.s. In the eight sec. $t^2=64$, $s=\frac{1}{2}\times 24 \times 64 = 768$ ft.

Velocity acquired by a Moving Point—(3) *To connect the velocity, acceleration, and distance, starting from rest.*—Drawing the same triangle AMP (Fig. 5) to represent the distance which a point traverses with an acceleration of a f.s.s. AM is, as before, the time t, MP the final velocity v or at. The

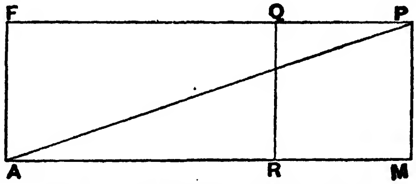


Fig. 5.—Distance and velocity, $v^2=2as$.

area of the triangle AMP is s, the space described starting from rest. Complete the rectangle MF, and draw MQ (the square on MP) $=v^2$. The rectangle MF is twice the distance s.

MP is a times AM by construction, so that MQ or v^2 is a times MF or $2s$. Hence

$$v^2=2as.$$

These important results, $s=\frac{1}{2}at^2$ and $v^2=2as$, should be noted for future use, and the graphic representation of them may be remembered as serving to impress them on the memory.

From the surface of the moon, where the acceleration is 12·2

c.g.s., a ball is projected vertically upwards with a velocity of 61 c.s., find to what height it will rise. In this case $v^2 = 3721$, and $a = 12{\cdot}2$; $3721 = 2 \times 12{\cdot}2 \times s$, so that $s = 152{\cdot}5$ centimetres.

Acceleration of Initial Velocity.—It is necessary also to consider the case of a moving point which has an initial velocity and acceleration.

(4) *To connect the space, time, and acceleration, starting with a given velocity.*—Let a point be moving with a velocity of u f.s., represented by a vertical line XA, and let a time t be represented by the horizontal line AM (Fig. 6). Then if there were no

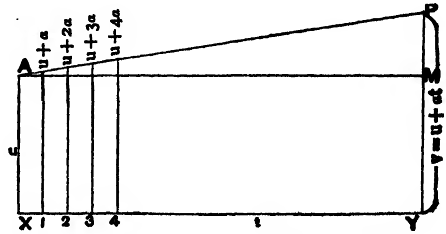


Fig. 6.—Acceleration of initial velocity, $s = ut + \frac{1}{2}at^2$.

acceleration the rectangle AY of area ut would represent the space which the point would traverse in t sec.

Divide the line AM into t equal parts representing the individual seconds, and draw vertical lines through the first four. If now an additional velocity a ft. per sec. be added in each second, the vertical lines representing the velocities must be increased by a, $2a$, $3a$. At M the velocity u or YM is increased by a piece MP or at representing the velocity added in t sec. Then AMP, as before, will represent the additional space described in consequence of the acceleration. The whole figure APYX represents the space described in t sec. by a point with initial velocity u and final velocity $u + at$ f.s. This area is $ut + \frac{1}{2}at^2$ ft., for the figure only differs from that in case (2) by the addition of ut, the space described due to the initial velocity. Therefore

$$s = ut + \tfrac{1}{2}at^2.$$

A body moving with uniform acceleration has a velocity of

6 ft. per sec. After an interval of $3\frac{1}{2}$ sec. it has passed over 54 ft. What is the acceleration? In this case the part of the 54 ft. due to the initial velocity is 21 ft.; 33 ft. are due to the acceleration, operating for $3\frac{1}{2}$ sec. $t^2 = \frac{49}{4}$.

$$\text{Since } s = \tfrac{1}{2}at^2,\ 33 = \tfrac{1}{2}a\tfrac{49}{4}, \text{ therefore } a = \tfrac{264}{49} = 5{\cdot}3 \text{ f.s.s.}$$

(5) *To connect the velocity, acceleration, and distance passed over, starting with a given velocity.*—Drawing the same figure, APYX (Fig. 7) represents s, the whole distance passed over; AM or XY, as before, representing the time t, XA the initial velocity u, and YP the final velocity v, *i.e.* $u + at$. Construct an exactly

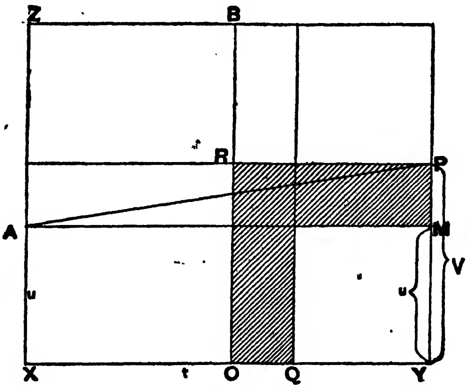


Fig. 7.—Distance and velocity, $v^2 = u^2 + 2as$.

equal figure PZ so as to complete a rectangle ZY, which is twice s. Construct MQ and PO, the squares on MY and YP, these represent the squares of the initial and final velocities, *i.e.* u^2 and v^2. The difference between these two squares is the shaded gnomon MRQ, which is equal to the vertical strip QB.

MP was made a times AM or XY by construction, and MP is equal to OQ, so that the strip QB is a times ZY. Therefore the difference of the squares, *i.e.* $v^2 - u^2$, is a times ZY or $2as$.

$$\mathbf{v^2 - u^2 = 2as.}$$

The square of the velocity is increased by twice the product of the acceleration and the distance passed over.

A stone was dropped from the top of a tower, and half a second afterwards another stone was projected downwards so as to reach the ground at the same instant as the first. If the second stone was moving 2 sec., what was the velocity of its projection and the height of the tower (acceleration 32 f.s.s.). The first stone was moving $2\frac{1}{2}$ sec., therefore the height of the tower is $\frac{1}{2}at^2 = \frac{1}{2} \times 32 \times \frac{25}{4} = 100$ ft. If it had had no initial velocity the second stone would have fallen $\frac{1}{2} \times 32 \times 4 = 64$ ft. in 2 sec., the residue, 36 ft., is due to the initial velocity

$$u = \frac{36}{2} = 18 \text{ f.s.}$$

The uniform acceleration of falling bodies is called g and is about 32 f.s.s. and 980 c.s.s. It will be further discussed in Chap. IV.

Summary.—The space described in t seconds by a point moving with a uniform velocity of v ft. or cm. per sec. is

$$v \times t \text{ ft. or cm.} \qquad (1).$$

The space described in t sec. by a point with an acceleration of a ft. or cm. per sec. in each sec. is seen to be

$$s \text{ ft. or cm., where } s = \tfrac{1}{2}at^2 \text{ if it start from rest} \qquad (2),$$

and

$$s = ut + \tfrac{1}{2}at^2, \text{ if the initial velocity be } u \text{ ft. or cm. per sec.} \qquad (3).$$

The velocity v ft. or cm. per sec. acquired by a point which has passed over a distance of s ft. or cm. while moving with an acceleration of a ft. or cm. per sec. in each sec. is given by

$$v^2 = 2as, \text{ if it start from rest} \qquad (4),$$

and

$$v^2 = u^2 + 2as, \text{ if it had an initial velocity of } u \text{ ft. or cm. per sec.} \qquad (5).$$

Parallelogram of Velocities.—A case often occurs in which a point has two different velocities, and the combination of these velocities must be considered. A simple example of this is seen in the effect of a current on the motion of a ship. Supposing, for example, that a ship be steaming 10 knots[1] E. b. N.,

[1] The expression 'so many knots' is an expression of speed or rate of motion. It represents so many nautical miles (6080 feet) run in one hour.

and at the same time a current be setting her 2 knots N. b. W., it is most desirable to know what effect this current will have on her motion over the ground, *i.e.* over the sea-bottom. The cases of the ill-fated *Serpent* and *Drummond Castle*, both carried by unsuspected currents setting into the Bay of Biscay, show that such a problem is of the first importance.

Plotting the case mentioned above on a chart, AB (Fig. 8) represents the ship's velocity (10 knots E. b. N.), AC the current velocity (2 knots N. b. W.). Completing the parallelogram, the two motions may be considered to take place one after the other. Thus if the vessel steam to B in half an hour, and then be carried by the current to D in the next half hour, the effect will be the same as if both motions took place in an hour. In either case she will find herself at D after an hour, and the true velocity over the ground will be represented in magnitude and direction by the diagonal AD (12·2 knots; E.N.E.).

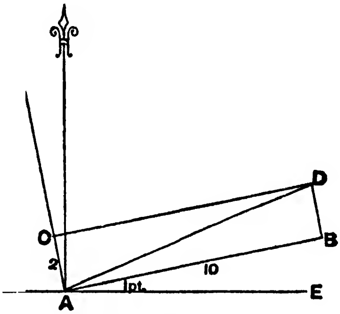


Fig. 8.—Current sailing.

This problem in current sailing is a very good example of THE PARALLELOGRAM OF VELOCITIES.—If a point be moving with velocities which are represented in magnitude and direction by the sides of a parallelogram which meet in a point, the diagonal through that point represents the resultant velocity of the point in magnitude and direction.

Raindrops, which in their fall have acquired a velocity of 40 f.s., strike the pane of a railway carriage moving at 40 miles an hour. At what angle will they slant upon the pane? A speed of 40 f.s. is equivalent to 27·27 miles an hour; solving the right-angled triangle, whose sides are 27·27 and 40, either by a protractor or by trigonometry, the angle is 34°17′ with the horizontal.

Resolution of Velocities.—The parallelogram of velocities

may be applied to resolve a given velocity into its components in different directions. If a line AD represents the velocity of a point in magnitude and direction, it is often necessary to know what proportion of it is effective in two different directions, *e.g.* horizontal and vertical.

Let AD (Fig. 9) represent the velocity of a stone thrown into the air; draw a horizontal line through A and a vertical line through D, meeting one another in B. Then the line BD represents the vertical part of the velocity at A which is affected, as we have seen in Newton's observation, by the acceleration of falling bodies. AD represents the horizontal part, which will not be so affected. This is called *resolving* the velocity horizontally and vertically.

Fig. 9.—Resolution of velocities.

A railway train is running through a tunnel at the rate of 30 miles an hour, when the boiler bursts, and a heavy piece of metal is thrown off at right angles to the direction of the train's motion and with a velocity of 33 ft. per sec. With what velocity will it strike the side of the tunnel? The train's speed is 44 f.s.; the metal's 33 f.s. The resultant velocity is 55 f.s. at an angle of 37° to the track.

Parallelogram of Accelerations.—Accelerations as well as velocities can be completely represented by straight lines. A straight line has magnitude and it has direction; the magnitude representing the number of units of velocity added per unit of time, and the direction being that of the acceleration, the straight line completely represents the acceleration.

Uniform acceleration alone being treated of, acceleration is velocity added in a unit of time. Hence it follows that the same considerations which led to the parallelogram of velocities lead also to the—

PARALLELOGRAM OF ACCELERATIONS.—If a point have two

accelerations, represented in magnitude and direction by the sides of a parallelogram which meet in a point, the diagonal through that point represents the resultant acceleration in magnitude and direction.

Trajectory (*trans, jacio*, the path of that which is thrown). A stone thrown into the air traverses a path which is called a *Trajectory*; this path can be determined by using the results now found.

If the velocity of projection be represented by AD (Fig. 9), the horizontal component (v) of the velocity at A, represented by AB, is uniform; after t sec. the distance s traversed horizontally $=v.t.$ The vertical component (u), represented by BD, varies in consequence of the acceleration of falling bodies; after t sec., the distance s' traversed vertically $=ut+\frac{1}{2}at^2$. If P be the stone or moving point, the vertical distance of P from a horizontal line AB $=ut+\frac{1}{2}at^2$, and the horizontal distance of P from a fixed point in AB $=vt$. A point moving thus describes a curve which is called a *Parabola*.

Though we can see no trace left in the air by a single body, such a path might be exhibited by making several bodies follow one another with equal velocities. The simplest way of effecting this is to project a jet of water with the required velocity; a jet is in reality a number of particles all issuing with equal velocity, and as each in turn follows the same path the form of the stream is the path of a single one.

A tall vessel is provided with a tap and a nozzle working on a joint (Fig. 10), so that it can be adjusted to any angle; a supply pipe is adjusted so as to keep the water at a definite height in the vessel. The course followed by the falling water may be traced on a blackboard placed near it, and will be found to be nearly a parabola; the resistance of the air to the motion of the water prevents its describing the true curve. When the whole apparatus is placed in a reservoir from which the air has been exhausted, the water follows a parabola.

Further, by the tap regulating the supply, it is possible to adjust the path of the stream so as to follow a curve described

on the board beforehand; the nozzle being placed as a tangent to the curve, the water in the tall vessel must be brought to and kept at such a height as will maintain the requisite velocity of outflow.

This experiment must be referred to again in the chapter

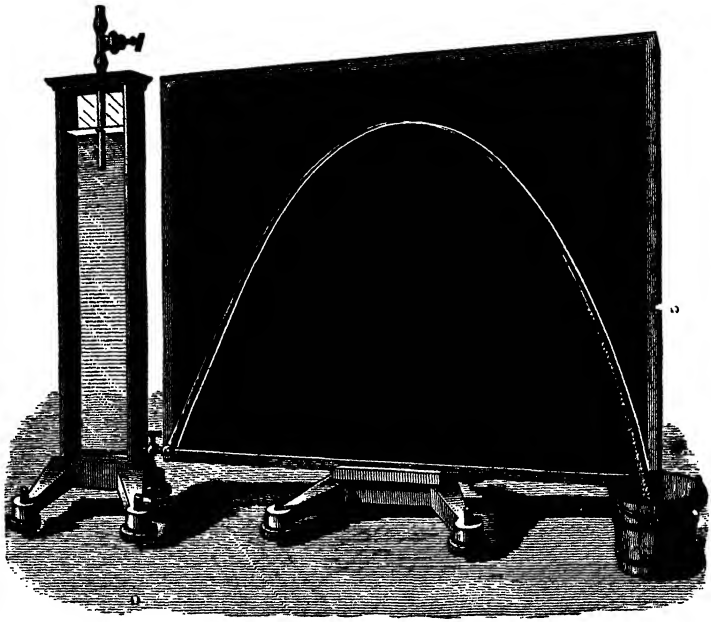


Fig. 10.—A trajectory curve.

on Moving Liquids (p. 239), but it illustrates the trajectory so perfectly, and the principles involved are so simple, that it is not out of place to introduce it here.

Motion in a Circle.—A motion which is really uniform also takes place when the direction of motion is uniformly changed, but not the speed. A ball swung round at the end of a string may be taken as an example of a point moving at uniform speed, but in a uniformly changing direction. Let it occupy after successive units of time the positions P and Q (Fig. 11), with

velocities at those points represented in magnitude and direction by the two equal straight lines PS, QT. These velocities, represented by the equal lines PS, QT, are equal in magnitude, but they are not in the same direction. This is a special case of uniform acceleration, equal speeds being added in a uniformly changing direction. To estimate the acceleration at the point P, take a very small unit of time, in which the ball moves to the next point of the circle. On the assumption that the space PQ traversed in a unit of time is small compared with AP, the

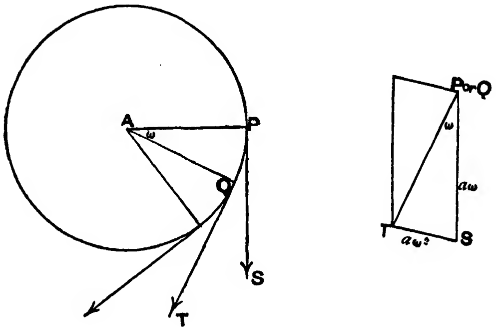


Fig. 11.—Motion in a circle.

acceleration is the change of velocity between the points P and Q, acceleration being the change of velocity in a unit of time.

The question then resolves itself into this: What velocity combined with PS will make QT? This is the acceleration at the point P. QT must be the diagonal of a parallelogram of which PS and the acceleration are two adjacent sides. To make the figure clearer, the lines are removed to the small figure on the right, where ST is seen to be the required acceleration. The letters, magnitudes, and directions are the same in the two figures.

It is usual to denote an angular velocity by ω, *i.e.* the angle which a radius a sweeps out in a unit of time is ω and the distance which its extremity traverses is $a\omega$. In the figure, PS is $a\omega$ and TPS is ω; the angle ω is so small that ST hardly differs

from the arc described with radius PS. The magnitude of the acceleration at P represented by ST is $a\omega^2$, and its direction is practically at right angles to PS. Now the line through P at right angles to PS passes through the centre. Hence when a point moves in a circle, radius a, with uniform angular velocity ω, the acceleration at any moment is $a\omega^2$ in the direction of the centre.

Motion of a Body.—At first sight we might gather that the motion of moving objects in general is very intricate. If a ball be thrown into the air the direction and the rate of its motion continually change. If a stick be thrown, its gyrations seem still more complicated. Now if the stick be watched attentively it will be seen that one point in it moves as a ball or stone would move, while the stick itself gyrates or rotates about an axis through this point. The ball has also a motion of the same kind; its centre describes a certain path in the air while the ball is spinning round an axis through the centre.

The rotation of a body round an axis may be measured by the angles swept out by a line in the body perpendicular to the axis. Its *angular velocity* is said to be uniform when equal angles are swept out in equal times.

Some moving bodies have no motion of rotation; the Newtonian apple had none. Some have no motion of translation; a fly-wheel, a top 'perfectly asleep,' are instances of rotation only. These are special cases in which the motion is of a simpler form.

The motion of a body at any instant is completely described by stating the velocity of translation of one point in the body, and the velocity of rotation of the whole body round an axis through this point.

The expressions motion, rest, uniform motion, etc., have now been discussed, and the terms velocity and acceleration have been introduced, explained, and defined so as to explain more definitely the ideas which they convey. Velocities and accelerations have been seen to be completely represented by straight lines, and the combination of velocities and accelerations to be effected by the simple principle that one who walks along the

diagonal of a parallelogram reaches the same point as one who traverses its sides.

In this chapter motion alone is treated of without reference to the causes of motion or the nature of the bodies moving. Kinematics, or the science of motion pure and simple, is studied first as an introduction to Kinetics, with which the next chapter is occupied.

CHAPTER II

Mass in Motion

Kinetics—Mass—Inertia—Momentum—Uniform Motion—Inertia Illustrated: Bodies at Rest, Bodies in Motion—Inertia of Rotation—Centrifugal Force—Force—Second Law of Motion—Standards of Mass—The F.P.S. System—The C.G.S. System—Units of Force—Representation of a Force by a Straight Line—Parallelogram of Forces—Impulses—Dynamics.

Kinetics.—By what has been said in the previous chapter about the motion of a point, and the connections which have been established between velocity, acceleration, time, and space described by a moving point, a certain language has been established which can be now used for describing the motion of bodies. The further consideration which must now be introduced is that of mass, for a body possesses mass and a point does not.

If two exactly similar bullets be moving, the one with a velocity of 1000 ft. per sec., and the other with a velocity of 2000 ft. per sec., the latter may be said to have a '*motion*' double that of the former. The bullets being equal, this may be nothing more than the speed or rate of motion treated of in the last chapter, where bullets were considered as moving points. But a new factor appears when the motion of a heavier or lighter bullet is considered. If two bullets be moving with a velocity of 1000 ft. per sec., one of them having twice as much lead in it as the other, it may be said to have twice the '*motion*' of the other, since there is twice as much lead moving at the rate of 1000 ft. per sec.

The '*motion*' here referred to is moving matter; the amount

of matter in a body is taken into consideration, every body being composed of some kind of stuff or matter.

Mass.—The mass of a body is the amount of matter in it. Matter is that which occupies space. The matter or stuff of a body is the body itself as nothing else about it is; its colour, its form, its size, its hardness, etc. are characteristics of the body, the matter composing it is the body itself.

Inertia (lit. *laziness*) is a name given to the property of matter described in Newton's first law, and it is only by comparison as to *inertia* that the magnitude of two masses can be compared.

The 'state of motion' referred to in Newton's first law of motion includes the amount of the mass as well as of the velocity with which it is moving. To prevent any misunderstanding, arising from the use of the general word 'motion,' the term '*momentum*' is applied to mass and velocity combined.

Momentum is the product of the mass of a body and its velocity. Unit momentum is the momentum of a unit of mass moving over a unit of length in a unit of time in a definite direction. Newton in his first law of motion stated the fact which he had observed in nature, namely, that momentum is unaltered except by force. Force is that which tends to alter momentum.

Uniform Motion in a straight line or unaltered momentum is not found in nature. Moving bodies always meet with impediments, but, the more the impediments are removed, the more uniform is the motion.

A stone moving over the surface of smooth ice affords an instance of motion to which little impediment is offered; still, the air and the ice both retard its motion to a certain extent. If these obstacles were removed its motion would never vary. Were a meteorite to traverse a space where there was neither resistance nor attraction, its momentum would be unchanged, and it would move on with the same speed in the same direction continually, and this would be uniform motion. Such conditions, however, do not exist.

Inertia Illustrated.—The apple at rest on a tree, the stone skimming over smooth ice have been instanced as examples. Some further experiments on, and illustrations of, inertia follow.

(i) **Bodies at Rest** continue at rest unless compelled by force to move. Relative rest is meant here; the foot-warmer, spoken of as relatively at rest, resists movement when it is kicked.

If a card be placed on a tumbler and a sovereign on the card, a smart fillip on the edge of the card may cause it to fly away, but the sovereign stops still, and, being unsupported, will fall into the tumbler.

The feat of sheep-slicing, so often performed at an assault-at-arms, illustrates inertia; the rapid pass with the sharp sword does not exert sufficient force to impart any motion to the hanging carcase.

(ii) **Bodies in Motion** retain their momentum unless constrained by force to alter it. If a person step out of a moving tram-car his body continues to move with the velocity it had in the car; his feet are stopped as they touch the ground, and he falls unless he step forward.

A horse is proceeding at full gallop across a heath: he suddenly finds himself on the edge of a sand-pit and brings up with both his fore-legs stiffened; his rider, unless he has a firm seat, will fly over the horse's head.

A hammer, a battering-ram, furnish instances of momentum employed to overcome resistance.

It is found in railway collisions that a Pullman car is very destructive to the carriages before it. The strong iron framing of the car maintains its momentum and acts like a battering-ram on the coaches in front.

Curling, the 'roaring game' of a Scotch winter, affords many illustrations of inertia. Stones weighing from 35 to 50 lbs. are played on ice with the object of placing them near to a fixed point or *tee* (Fig. 12). Force is required to start the heavy stone. When delivered, it flies over the smooth ice with what appears at first to be a uniform motion; gradually it loses its

speed, and the *skip* or head of the side estimates its chances of reaching or passing the *tee.*

The players each have a broom, and if the stone lags on its journey he calls 'Gie him heels!' and the brooms polish the ice before it; if it goes too fast, he shouts 'Besoms up!' and the snow and ice chips check its progress. Were there perfectly smooth ice and no air to destroy its momentum, the stone would retain it unaltered.

Fig. 12.—Curling.

The motion of a body was defined on p. 20 as consisting of the velocity of translation of one point in the body, and the velocity of rotation of the whole body round an axis through the point.

Inertia of Rotation.—If a body be rotating round an axis it will continue to rotate round the same axis with the same uniform angular velocity unless constrained by force to change it. The earth rotates on its axis with uniform angular velocity in one sidereal day. In strict accuracy this should be called 'approximately' uniform; there is a very small retardation due to the friction of the tides, and a small change in the direction of the axis, due to the attraction of sun and moon. These are too minute to be considered, and the rotation of the earth can be looked on as our nearest example of the permanence of angular momentum. The direction of the axis and the angular velocity

continue unchanged; its angular velocity affords a standard of time.

Advantage is taken of inertia of rotation in the use of a heavy fly-wheel in machinery. Its inertia controls the shafting by maintaining a nearly uniform motion when the work done by the machines varies.

Centrifugal Force (or a tendency to *fly from the centre*) is an instance of the effect of inertia.

If a stone be whirled round the head in a sling, its velocity is continually changing (see p. 7), even though the speed be uniform. Its momentum is therefore continually changing, and this must be due to force—the force applied to the stone by the sling. When the stone is released, and this force no longer acts upon it, it pursues a path with the velocity which it had at the moment of release. This has the direction of the tangent to its circular path (Fig. 13). The stone, instead of continuing the circular path from A to B, goes from A to C in the same time, that is, being released it has gone to C instead of going to B, which makes it appear to fly from the centre.

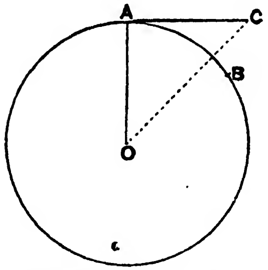


Fig. 13.—Centrifugal motion.

The drops of water flung off from a mop when it is twirled round start in the direction of tangents to the circular outline of the mop. They have the appearance of flying away from the centre.

A stationary engine is often regulated by a *governor*. Two heavy balls are fastened to arms, hinged, as in a semaphore, on a vertical axis, which turns with the revolution of the engine. When the speed of the engine increases the balls fly outwards, and, by a connection with the throttle valve, cut off the supply of steam, and the speed diminishes. The governor balls then fall and approach the axis, and steam is again increased. The object of the governor is to keep the engine running at a uniform speed by adjusting the supply of steam to the load.

The whirling table in a lecture room affords many experiments exhibiting 'centrifugal force.'

A ball, or, as in Fig. 14, two balls connected together, slide on a brass rod which is rotated about a vertical axis. If the single ball be placed at the centre of rotation it will remain there; but it is difficult to place it exactly at the centre, and, as the rotation continues, if it be displaced at all from the centre, it flies with great violence to the outside.

In Fig. 14 is also shown a brass axis carrying thin strips of

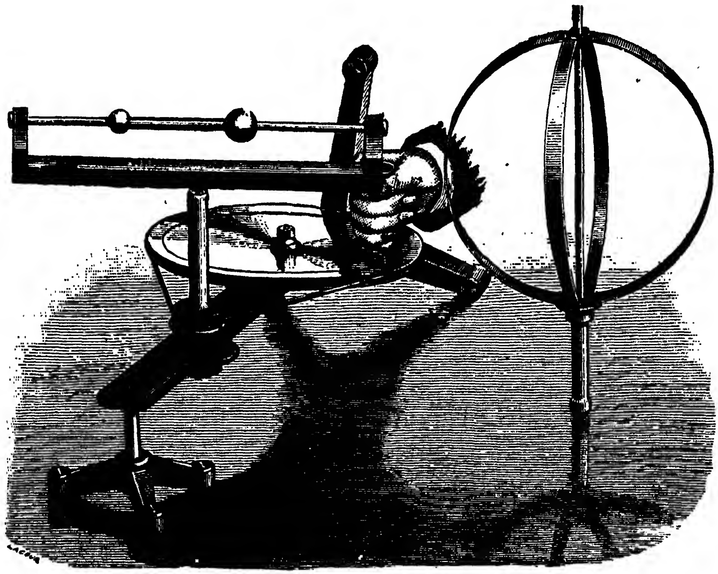


Fig. 14.—Ball and 'figure of the earth.'

metal in the form of two circles at right angles; the strips are fastened at the foot of the axis, the upper parts slide on the rod. If this be screwed on the spindle of the whirling table, the circles become flattened when rotated, since the particles of metal endeavour to continue their rectilinear motion. The experiment suggests the idea that the flattened form of the figure of the earth is due to its rotation in a more or less fluid condition. In

another experiment a glass globe, not quite filled with water, is screwed on to the whirling table; as the rotation proceeds the water revolves in a fluid ring (Fig. 15), leaving an almost cylindrical core of air.

This form of apparatus shows the action of a cream separator. Milk is placed in a drum revolving on a vertical axis. A rapid

Fig. 15.—Instantaneous picture of fluid ring.

rotation divides the heavier milk, which flies to the outer rim, from the lighter cream, which forms the inner surface of the cylinder. The cream is separated by removing the inner layer of the rapidly revolving ring of fluid.

'Centrifugal force' is the force exerted by a whirling body on the connection which obliges it to move round a centre; it is the reaction which the inertia of a body constrained to move in a circle opposes to the constraining force. Bodies which are moving in a circle have an acceleration $a\omega^2$ in the direction of the centre; to make a body move in a circle force must be exerted on it towards the centre of the circle. If this force were not exerted the body would fly from the centre.

If this be understood, the term 'centrifugal force' will not be misleading.

Force as described in the first law is that which tends to change momentum. If a body which is free to move be acted upon by a force, whether it be at rest or in motion, its velocity is changed by the force by a certain definite amount at the end of a unit of time. If an equal force act on a similar body for a unit of time it will produce the same change of velocity, and so on with any number of equal forces and bodies. Now if the bodies were all fastened together, and the equal forces all acted on them in the same direction, the bodies would all experience the same acceleration. This shows that in order to impart the same acceleration the force must be proportional to the mass of the body.

If, again, there be a body whose velocity is changed by a certain amount when a force has acted on it for a unit of time; a second equal force also acting on it produces an equal acceleration; and if any number of equal forces act simultaneously on it in the same direction, the total acceleration is the sum of all the accelerations. The acceleration produced by them all is the same multiple of the original acceleration as the total force is of the original force.

Hence we conclude that the force required to produce the same acceleration must be proportional to the mass of a body; also that, the body being the same, the acceleration imparted to it must be proportional to the force applied. Combining these two considerations, it follows that the magnitude of a force can be measured by the change of momentum in unit time. This is the substance of **Newton's Second Law of Motion.** *Change of motion is proportional to the force applied, and takes place in the direction of the force.* Force is measured by change of momentum per sec. in magnitude and direction, or by the product of the mass and the acceleration imparted to it; so that if P be the force which imparts an acceleration f to the mass m; then $P = mf$.

It must be observed that Newton omits to notice the *time* during which the force is acting. The law should begin, 'During the same time, change of motion, etc.'

In dealing with the same body, that is, with the same inertia, the force applied varies as the acceleration, and the acceleration varies as the force. For example, if a body be falling through treacle with a velocity of 10 centimetres per second, and at the end of one second it be moving with a velocity of 4 centimetres per second; or again if when the same body has fallen through water its velocity be 7 centimetres per second after one second,—in the former case there is a negative acceleration of six units, and in the latter of three units. We conclude, therefore, that as the loss of momentum in the treacle is twice that in the water, the force retarding the motion of the body in treacle is twice that in water, and both in the direction opposite to its fall.

Mass, force, and acceleration are seen to be quantities which are connected with one another. If we wish to measure mass, we can do so by estimating the acceleration which would be imparted to it by force; if we wish to measure force, we can estimate the amount of acceleration which it would impart to a mass.

It is true that the idea of force is not necessarily connected with mass and acceleration. When a heavy weight rests on a table we know that the table is exerting a force to support it, because if we take the weight in our hands we have to exert a muscular force to support it. In the compression of a spring, the extension of animal muscle, the resistance to expanding steam or compressed air, force is exerted without any change of momentum. It would be possible to establish a standard of force by making with great care a standard steel spring, which the unit force should compress through unit distance. Springs are used in practice for measuring force.

But for a scientific standard of force it is necessary first to establish a standard mass; the unit of force is then that force which produces unit momentum in unit time, or imparts unit acceleration to unit mass. The discussion of measures of force must, therefore, be deferred till after the measures of mass have been discussed.

Standards of Mass.—Two standards of mass are generally used.

The British Pound is the mass of a piece of platinum, of which Fig. 16 is the exact shape and size; this is kept in the Standards Department of the Board of Trade as the legal standard for Great Britain. It contains 7000 grains.

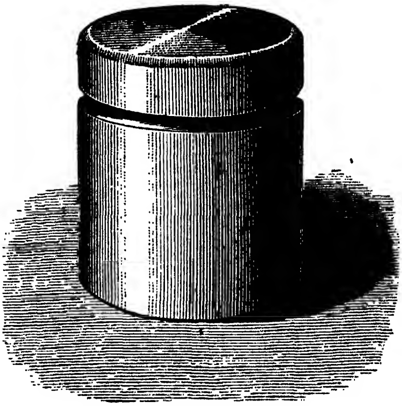


Fig. 16.—The British pound.

The Kilogramme is the mass of a piece of platinum, of which Fig. 17 is a careful representation; this is kept in the Bureau des Archives in Paris, and is the standard of mass for the metrical system. A copy of this Standard is also kept in the Standards Department.

Fig. 17.—The kilogramme.

1 kilogramme = 1000 grammes. 1 gramme = 1000 milligrammes.

Comparison—

1 lb. = ·4536 kilo. 1 kilo. = 2·2046 lb.

The comparison of quantities measured by different units is facilitated by the use of the scales given on pp. 103, 105.

The F.P.S. System.—In the British scientific system of units

The Foot is taken as the Unit of Length.
The Pound is taken as the Unit of Mass.
The Second is taken as the Unit of Time.

This combination of units is called *the F.P.S. system.*

The C.G.S. System.—The Gramme is the unit of mass most frequently employed for scientific purposes: it is the one-thousandth part of the standard kilogramme. It was intended originally to be the mass of one cubic centimetre of distilled water at 4° C.; a reference to Fig. 72 (p. 102) shows that one gramme of distilled water occupies less than a cubic centimetre at a temperature of 4° C. The mass of a cubic centimetre at that temperature is really 1·00013 gramme, but for all practical purposes it is one gramme.

The metrical system is well adapted for scientific investigations, and in this—

The Centimetre is taken as the Unit of Length.
The Gramme is taken as the Unit of Mass.
The Second is taken as the Unit of Time.

This combination of units is called *the C.G.S. system.*

Units of Force.—The Poundal, the British scientific unit of force, is that force which will produce a velocity of one foot per second in a mass of one pound after acting on it for one second.

The Dyne or C.G.S. unit of force is that force which will produce a velocity of one centimetre per second in a mass of one gramme after acting on it for one second.

The dyne is inconveniently small for measuring ordinary forces; the megadyne, 1,000,000 dynes, is sometimes used.

These are the scientific units of force which are convenient

for theoretical investigations; the practical unit of force—THE WEIGHT OF ONE POUND—will be discussed later (p. 48).

Representation of a Force by a Straight Line.—Since a force tends to impart acceleration to a mass, and the force is proportional to the acceleration in magnitude and coincides with it in direction, it follows that forces may be completely represented by straight lines equally with velocities and accelerations (pp. 7, 16). Two straight lines through a point can completely represent two forces acting on a mass at that point, when their lengths are proportional to the accelerations they would each impart to it, and their directions are the same as the directions of the forces.

It follows that the parallelogram law, which was seen to hold good for velocities and accelerations, also holds good for forces.

Parallelogram of Forces.—If two forces acting at a point are represented in magnitude and direction by the sides of a parallelogram which meet in the point, the diagonal through that point represents the resultant force in magnitude and direction.

One of the simplest cases, and one in which problems continually occur, is that of forces at right angles. The force which is represented by the diagonal of a rectangle may be replaced by two forces represented by adjacent sides of the rectangle.

For example, the force of wind acting on a sail OP (Fig. 18) and represented by AC is 'resolved' into a force AD along the sail, which does not produce any effect, and the force AB perpendicular to it, which does. This force AB is composed of two parts, AE and AF, of which one AE propels the ship, while the other AF causes 'leeway,' *i.e.* makes the ship go sideways.

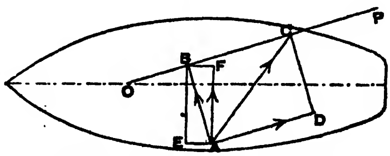


Fig. 18.—Sail of boat on port tack.

Impulses.—Change of motion is sometimes caused by forces which are very great and act for so short a time that they cannot be seen to produce acceleration. If a body in motion

meets another, and an impact occurs, a change of motion takes place, which, for all practical purposes, may be called instantaneous. Sudden change of momentum is called an impulse.

A billiard ball struck by a cue or by another ball has the appearance of starting at once with a velocity depending on the impact.

Two equal ivory balls are suspended by strings (Fig. 19) of equal length. One of them A is drawn aside and let go, so as to hit the other B. As a consequence of their impact B, which was before at rest, is set in motion with a velocity almost equal to that which A had at the impact, and B rises to a height almost equal to that from which A was released. The amount of motion set up in B is equal to that which A had, and A remains perfectly still until it is hit again by B. The change in the momentum of B measures the impulse of A impinging on B. It should be observed that in this experiment the equality of the two masses is tested absolutely by the equality of their inertia.

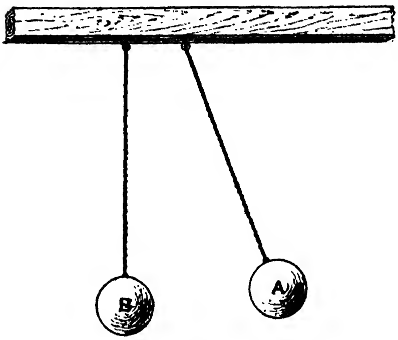


Fig. 19.—Impact.

Dynamics (*δύναμις*, *dynamis*, force) is the name given to the study of the action of force on bodies; it has two branches: Kinetics, the study of the action of force on moving bodies; and Statics, of the action of force on bodies at rest and remaining at rest.

CHAPTER III

WORK DONE AND ENERGY

Work Done—Units of Work—Energy—Potential Energy—Kinetic Energy—Momentum: Work done and Kinetic Energy—The Gun and Shot—Transformation of Energy—The Pendulum—The Conservation of Energy—The Earth—A Conservative System.

Work Done is defined in Mechanics as the exertion of force through a distance in its own direction. In ordinary affairs much work is done which cannot be so described. If a bucket of water be carried along a level path no 'work is done' against the weight of the water; yet the popular impression would be that a good deal of work is done if much water be carried, even though the path be level. The expression 'work done' is a technical one, and is confined to the exertion of force through a distance in its own direction, and it is measured by the product of the force and the distance moved in the direction of the force.

If a boat be towed on a river behind a steam-launch, and a spring-balance fastened to the tow-rope indicate the force exerted on the boat, the product of this force into the distance through which it is exerted is the measure of the work done on the boat. If the boat be aground on a sandbank and the launch engaged in towing it off, no work is done on the boat until it moves; the spring-balance would indicate a certain force as exerted, the engines are doing work on the water, but 'no work is done' on the boat so long as it remains at rest.

Units of Work.—The FOOT-POUNDAL is the amount of work

done by a force of one poundal in acting through one foot in its own direction.

The ERG is the C.G.S. unit of work; it is the work done by a force of one dyne in acting through one centimetre in its own direction.

The erg is too small a unit for practical purposes; one million (10^6) ergs are called a megalerg or megerg; but the more usual unit is the JOULE, which is 10 million (10^7) ergs.

The FOOT-POUND is the practical unit of work, which will be discussed later (p. 51).

Energy is capacity for doing work. Living creatures have a capacity for doing work, but the subject of Natural Philosophy does not include the study of the manner in which living creatures develop energy; this chapter deals with the manner in which inanimate bodies have capacity for doing work.

The Potential Energy (lit. *possible energy*) of a body due to a force is the capacity for doing work which it possesses in consequence of its position with respect to that force.

A stone resting on the edge of a cliff has potential energy due to gravity; springs or gases compressed, weights raised, water so placed that it can fall through some height, all have capacity for doing work owing to their position with respect to force. The potential energy of a body can be measured by the amount of work done against the force which had to be overcome to place it in its present position; this is the amount of work which it can do when released.

Potential energy is measured in foot-poundals or ergs.

The Kinetic Energy (lit. *energy of motion*) of a body is the capacity for doing work which it possesses in consequence of its mass and its velocity; it is equal to the work which has been done to impart this velocity to the mass.

A force of mf poundals (or dynes) imparts an acceleration f f.s.s. (or c.s.s.) to a mass of m lbs. (or gr.). If it act for t sec., it imparts to m lbs. (or gr.) a velocity $v=f.t$ f.s. (or c.s.), and the mass moves through a distance $\frac{1}{2}f.t^2$ ft. (or cm.). The work done by the force is the product of the force, and the distance

through which it has acted $= mf \times \frac{1}{2}ft^2 = \frac{1}{2}mf^2t^2$ ft.-poundals (or ergs).

Let the velocity $f.t$ be replaced by v; then the work done by the force is $\frac{1}{2}mv^2$ ft.-poundals (or ergs). Conversely, this is the work which a body of mass m can do in consequence of a velocity v, and is called its *Kinetic Energy.*

Momentum: Work Done and Kinetic Energy.—If a mass of 100 lbs. (or gr.) which is free to move be acted upon by a force of 1000 poundals (or dynes), the acceleration is 10 f.s.s. or c.s.s.; after one sec. it moves with a velocity 10 f.s. (or c.s.).

The *momentum* produced by the force in one sec. is $100 \times 10 = 1000$ F.P.S. (or C.G.S.) units.

The mass moves in one sec. through a distance 5 ft. (or cm.) ($s = \frac{1}{2}at^2$; $5 = \frac{1}{2} \times 10 \times 1$).

The work done by the force is the product of the force, and the distance moved $1000 \times 5 = 5000$ ft.-poundals (or ergs), and this is equal to half the product of the mass and the square of the velocity $= \frac{1}{2} \times 100 \times 100 = 5000$ ft.-poundals (or ergs), *the kinetic energy* of the moving mass.

Now let another body of half the mass 50 lbs. (or gr.), also free to move, be acted on by the same force 1000 poundals (or dynes) for one sec., it moves with a velocity 20 f.s. (or c.s.).

The *momentum* produced is $50 \times 20 = 1000$ F.P.S. (or C.G.S.) units, the same as in the former case.

This mass moves through a distance of 10 ft. (or cm.) ($s = \frac{1}{2}at^2$; $10 = \frac{1}{2} \times 20 \times 1$).

The work done by the force is the product of the force, and the distance moved $= 1000 \times 10 = 10{,}000$ ft.-poundals (or ergs), which is the same in value as the *kinetic energy,* half the product of the mass and the square of the velocity $= \frac{1}{2} \times 50 \times 400 = 10{,}000$ ft.-poundals (or ergs). Hence the work done on, and kinetic energy imparted to, the mass of 50 lbs. (or gr.) is twice that done on a mass of 100 lbs. (or gr.) by the same force in the same time.

If the same force act on a mass of 10 lbs. (or gr.) for one sec. it produces the same momentum, 1000 F.P.S. (or C.G.S.) units,

but it produces a velocity 100 f.s., and so the kinetic energy produced is $\frac{1}{2}mv^2 = \frac{1}{2} \times 10 \times 10{,}000 = 50{,}000$ ft.-poundals (or ergs), which is also the work done on it—ten times that done on the mass of 100 lbs.

These three examples illustrate the general principle that, if a force act on any mass which is free to move, the momentum produced in the same time is the same; but the work done by the force and the resulting kinetic energy produced vary inversely as the mass of the body.

The acceleration imparted by a given force varies *inversely* as the mass on which it acts; the distance through which the body is moved in a given time varies as the acceleration directly. Hence the distance moved and the work done by a force in a given time vary *inversely* as the mass on which it acts.

The Gun and Shot.—The comparison between the work which is done by the same force on large and small masses may be illustrated by an imaginary instance of a shot fired from a big gun. It may be assumed that an equal force acts on the gun and on the shot, remaining uniform during the time that the shot is in the muzzle of the gun. Both receive equal momentum, but in opposite directions.

But the work done and the kinetic energy imparted vary inversely as the masses of gun and shot.

If the mass of the shot be 100 lbs. and of the gun (6 tons) 12,000 lbs., though the gun and the shot have equal momentum the kinetic energy of the shot is 120 times that of the gun.

While the shot is in the muzzle of the gun, it moves 120 inches in the time the gun is only moving one inch, so that the work done by the expanding force of the powder, supposed to be uniform, on the shot is 120 times that done on the gun.

If the work which they respectively do in consequence of their kinetic energies be compared, the practical meaning of the expression kinetic energy can be seen.

The gun is brought up by the controllers, which may be

supposed to exert a uniform force on it through a certain distance; its momentum is thus destroyed. The shot may be supposed to meet with an equal uniform force in the resistance of armour and backing; its momentum is destroyed in the same time, but owing to its velocity it goes 120 times as far in the time, and therefore does 120 times as much work. The shot pierces 120 inches of armour and backing, while the gun has only moved one inch, both assumed in this imaginary case to be against equal forces. The kinetic energy of the shot, the work which it can do, is 120 times that of the gun from which it is fired.

The momentum which a force produces in one second is the same on whatever mass it acts. If a small force act on a large mass it produces a very small movement, hence the work which it does is very small. This may help the student to understand why a force meeting with resistance from a body supposed not to move does no work. It is as though it acted on a mass supposed to be infinite, in which it produces no movement, and so no work is done.

Transformation of Energy.—In the examples given previously, force has been supposed to be acting on a body free to move, and the work done has produced only kinetic energy. If however other forces be acting, work done against force may give a body potential energy, so that it can do work and impart kinetic energy.

If a railway carriage be standing close to terminal buffers, and a train be backed down on it, the buffer springs are compressed and work is done. The carriage itself then has potential energy, and when the train goes away does work on the train by pushing: could the train be instantly removed the carriage itself would acquire kinetic energy.

This is most simply seen in the case of a pendulum ball and its movements due to its weight. Gravity, the attraction of the earth, is considered in the next chapter; for the present it is sufficient to speak of it as the cause of that force which we call weight.

The Pendulum.—When a suspended ball is drawn aside, it is raised, *work is done* against gravity, measured by the product of the weight of the ball and the height s (Fig. 20) through which it is raised. Before it was disturbed the ball was in equilibrium, at rest in its lowest position; when held on one side it is at rest, but work has been done on it, and its condition is changed. This can be seen by releasing it; when it reaches its lowest position again work has been done on it by gravity,—as much work as was done on it against gravity to raise it. It is not now at rest in its lowest position, as it was initially, but moving as fast as it would be moving if it had fallen freely through a vertical height s. Moving on, it rises again to a height equal to that from which it was released; it is then at rest again.

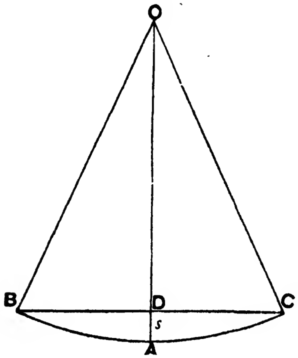


Fig. 20.—Simple pendulum.

Were a ball thrown up vertically with the velocity v of the ball at its lowest point, it would reach a height s, be at rest there, then fall again and obtain the same velocity where $v^2 = 2gs$.

The work done on the pendulum ball in pulling it aside and so raising it has changed its condition; in its lowest position it is no longer at rest, but moving with a certain velocity which enables it to do work against gravity by raising its own mass through a certain height or another equal mass if it were to collide with it, as in Fig. 19.

In fact, the work done on the pendulum ball has endued it with energy. This energy is of two kinds: there is the energy which it possesses when at rest in its highest position; this is called Potential Energy, or energy *possible* because of its position; and there is the energy which it possesses in virtue of its motion, called Kinetic Energy or Energy of Movement.

The motion of the ball is continually varying; sometimes

the ball has more energy of movement, sometimes more energy of position, neither of which it had before work was done on it.

When the pendulum ball is in regular oscillation potential energy is continually being exchanged with kinetic energy. As the ball is falling its potential energy is decreasing and its kinetic energy is increasing, till at the lowest point there is no potential energy; the kinetic energy is then a maximum, and equal to the potential energy at the point of release.

The opposite takes place as the ball rises; its potential energy continually increases, while its kinetic energy decreases and vanishes when the position of rest is reached again; then its potential energy equals the work done on the ball in the first instance. The sum of the two forms of energy remains the same so long as no work is done on the body from outside.

Just as coins of one country exchange in another at a certain rate of exchange, so the rate of exchange of work done, potential energy and kinetic energy, measured in foot-poundals or ergs, is—

$$\begin{aligned}\text{Work done} &= \text{force} \times \text{distance} = \text{change of potential energy} \\ &= \text{change of kinetic energy} = \tfrac{1}{2}\ \text{mass} \times \text{change of velocity}^2.\end{aligned}$$

For the complete consideration of the kinetic energy of a body the movement of translation and the movement of rotation must be separately considered.

The kinetic energy of translation of a mass m moving with velocity v is $\frac{1}{2}mv^2$ foot-poundals or ergs.

The kinetic energy of rotation of a body is $\frac{1}{2}mk^2\omega^2$, when ω is the angular velocity about an axis and k the distance from the axis at which the mass of the body might be placed to require a couple of moment equal to that which the body requires to turn it.

Kinetic and potential energy together constitute the total energy of a mass or a system of bodies; they may be changed the one into the other, but taken together their sum is constant. This is called the **Principle of the Conservation of Energy.** The total energy of a system of bodies is constant; kinetic energy may be turned into potential energy or the reverse, none is lost.

If work be done on the system its energy, whether potential or kinetic, is changed to that extent, and also if the system does work or communicates energy to bodies outside it.

The pendulum observation furnishes a good example of this. Were the motion in a vacuum and the string perfectly flexible, the ball would return to the same height and the oscillation would never change. But the air retards the ball, work is done on the air, and the energy so imparted to the air is transferred to the neighbouring air and so lost to the system with which we began—the ball and string; in the end all energy is thus removed and the ball comes to rest. But energy is not lost to the universe, and the sum of energy in the universe is constant.

The Earth.—An illustration on a larger scale may be found in the motion of the earth round the sun. The attraction of the sun causes an acceleration of $\frac{10}{45}$ inch s.s. in the earth in the direction of the line between them. In the winter the earth is about $3\frac{1}{2}$ million miles nearer the sun than in the summer; the earth has moved through that distance towards the sun. The force of the sun's attraction has done work on the earth through that distance, and in consequence the kinetic energy of the earth is increased to that extent. The product of the earth's mass, the acceleration $\frac{10}{45}$ inch s.s., and the distance $3\frac{1}{2}$ million miles is the work done on the earth. The velocity of the earth in its orbit, about 18 miles per second, is increased by about $\frac{1}{2}$ mile per second. The product of the earth's mass and the change in half the square of the velocity is the change in the kinetic energy of the earth in its orbit.

In what has been said there is a good deal of repetition, but the subject of energy is worth some trouble to master, and this must excuse reiteration of the same ideas.

It is only of late years that the principle of the conservation of energy has been seen to be of universal application. Later on it will be seen that heat and sound and light, magnetism and electricity are all forms of energy, and these must be taken into consideration when the total energy of a system is estimated. For example, in old times it was thought that motion was lost

through friction, but the work of Joule and others has enabled a numerical equivalent to be assigned to the work done by friction, and changed into the energy of heat. All this must be more fully treated of later.

In Mechanics the principle of the conservation of energy can be studied as applied to smooth bodies, and omitting friction. Such a system is called **a Conservative System**, which is one in which the work done is equal to the changes in potential and kinetic energy, and is independent of the order of the changes.

CHAPTER IV

Gravity and Weight

Gravitation—Gravity—The Fall of Bodies—Fall Apparatus—The Earth's Attraction Varies—Value of *g*—Weight—Weight of One Pound—Units of Force—A Force of W Pounds—The Foot-Pound—The Pile-Driver—Hammers—Power—Units of Power.

Gravitation. — Newton's observations led him to conclude that every particle of matter in the universe attracts every other, and that this was the cause of the motion of the heavenly bodies as well as of the apple. This conclusion is borne out by the fact that the moon and planets do in reality move in paths which correspond to such an attraction. The earth attracts the apple and the apple attracts the earth; so also the sun, moon, and earth attract one another, in proportion to their masses and inversely to the square of their distances.

Gravity.—In considering the fall of bodies near the earth, the mass of the earth is comparatively great and the distances of falling bodies from its surface are small compared with their distances from its centre. Hence we can assume without error that the earth's attraction at the same place does not change as the body falls. The attraction of the earth is called *Gravity.*

The Fall of Bodies.—The early philosophers thought that small bodies must fall more slowly than larger ones. Galileo put this to experimental test by dropping various weights from the top of the leaning tower of Pisa. He found that when let fall simultaneously they reached the ground almost at the

same time, whatever their size. The difference observed in the case of bodies of lighter substance he rightly judged to be due to the resistance of the air. That this is the case may be shown by the experiment (Fig. 21) usually called the guinea and feather experiment.

A coin and a feather are placed in a long tube closed at both ends, and then all the air is exhausted. Now, ordinarily, if a feather and a coin are let fall together, the coin falls quickly, while the feather flutters to the ground. But in the tube devoid of air both objects fall together, showing that the attraction of the earth causes an equal acceleration in all bodies, and that any difference in the rate of fall is due to the air.

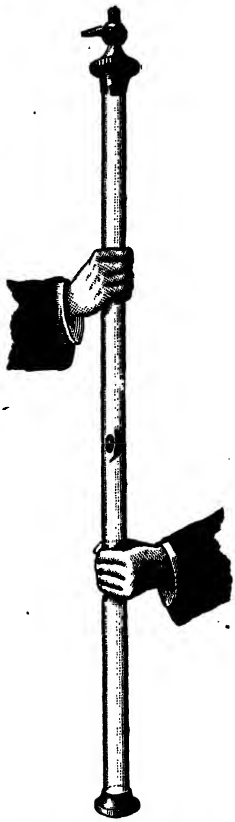


Fig. 21.—Guinea and feather tube.

Fall Apparatus.—The fall of bodies to the earth is so rapid, that it is difficult to observe the time taken and the velocity acquired. Professor Barrell has devised an apparatus (Fig. 22) for observing the time of fall through any given distance. Small iron balls are fed by a glass tube to the slider A, which, in the position of rest, presents in front of the tube a hole which exactly holds one ball.

A current of electricity is sent through the circuit of wire and the coils B and C become magnets; C attracts its core D and raises the slider A. When the hole and ball in it reach the spout E, the ball rolls out through E and is held by the electro-magnet B. When the circuit is broken the ball is let fall; the slider also returns to the position of rest, to pick up another ball. The circuit being closed again, the same operation is repeated. The balls fall from B on to a plate Z placed at any

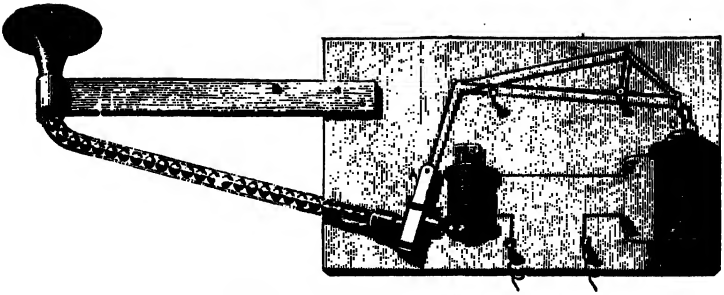
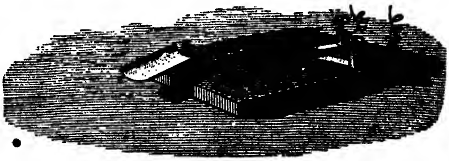


Fig. 22.—Barrell's fall apparatus.

required distance below B; the impact of the ball on the plate raises the far end of the lever, breaks the circuit for a very small fraction of a second, and so instantaneously releases the next ball to fall through the same distance, and at the same time works the slider A which feeds another ball on to the electro-magnet B. With this apparatus the whole time taken in a large number of successive falls can be observed, and thence the time of an individual fall, even over a short distance, can be accurately deduced. Let 20 balls in succession be set to fall through 9 feet, the time taken is 15 seconds in all; therefore the time of fall of each is ·75 second. The same operation being conducted with a fall of 12 feet, it is found to occupy ·86 second; and with 16·1 feet to occupy one second, for each ball.

The accurate working of the apparatus should be tested by recording the interval occupied by the fall of various numbers of balls from time to time during the experiment.

It was found in the last chapter, that with acceleration a the space s described from rest in a time t is given by $s = \frac{1}{2}at^2$. The distance and time of fall due to gravity are measured by this apparatus; the acceleration due to the earth's attraction can therefore be ascertained by it. As the distance allowed for the fall may be moderate, the balls need not acquire a high velocity, and the resist-



ance of the air does not then seriously affect the time of fall; thus the value of the acceleration of gravity is obtained with considerable accuracy.

The Earth's Attraction Varies.—There are two causes which alter the attraction of the earth on bodies at different points on its surface: (1) The earth is not spherical in shape, and places on the equator are farther from the centre than other places; (2) the 'centrifugal force' of bodies due to the earth's rotation is greatest at the equator. Both these causes make the earth's attraction less strong at the equator than elsewhere, so that the acceleration which it causes increases gradually from the equator towards the poles.

Value of g.—The acceleration due to gravity is usually called *g*.

The following table gives the values of *g* at various places on the earth's surface, the accelerations being given in f.s.s. and in c.s.s., for a body falling in vacuo.

	Latitude.	Value of *g* in cms.	Value of *g* in feet.
Equator . .	0°0′	978·10	32·09
Latitude 45° .	45°	980·61	32·17
Paris . . .	48°50′	980·94	32·18
Greenwich . .	51°29′	981·17	32·19
Pole . . .	90°	983·11	32·25

The acceleration of gravity depends on the earth's mass. If the body were falling to Jupiter from a point near it, its acceleration would be about 30 *g*; if it were falling to the moon from a point near to its surface, the acceleration would be $\frac{1}{12}$ *g*.

Weight.—The conclusion to which Galileo's experiments led was that, but for the air, all bodies would fall at the same rate, or, in other words, that the change of momentum of a falling body varies as its inertia. A body falling freely from rest acquires a velocity of *g* feet per sec. after one second in consequence of the

attraction of the earth. The product of its mass and this velocity gives the momentum which has been acquired in a unit of time. This is the measure of the force which has been acting upon it, which we call the weight of the body. The weight of a body is the force with which the earth attracts it, and as this force varies with the inertia of the body it follows that the method of weighing, which consists of balancing this force, is a correct mode of estimating the mass of the body.

The weight of one pound at Greenwich is a force which produces 32·19 F.P.S. units of acceleration in a mass of one pound. Therefore the weight of a pound at Greenwich is 32·19 poundals.

The weight of a gramme at Greenwich is a force which produces 981 C.G.S. units of acceleration in a mass of one gramme. Therefore the weight of one gramme is 981 dynes.

The attraction which the earth exerts on all bodies provides the practical unit of force, which is most frequently used in Great Britain.

THE WEIGHT OF ONE POUND is the force which the earth exerts on a mass of one pound. It is the force which imparts to a mass of one pound the same acceleration which the attraction of the earth communicates.

The British pound is a unit of mass. The weight of a pound is the force of the earth's attraction on it, and is the practical British standard of force. What is called in common parlance a 'pound weight' is really a measure of mass used in shops to weigh out 'so much' of any article, so much stuff or matter, whether of sugar or of paper. To whatever part of the world it be taken it will always be a 'pound weight'—so much brass or iron, a unit of mass; but the earth will not exert on it the same force at all places.

At the equator its weight would be a smaller force; if it falls freely, its weight (the earth's pull on it there) after one sec. causes a change of momentum of 32·09 lb. f.s. instead of 32·19 at Greenwich. At the poles the earth would attract it more strongly (g is larger), and would cause a change of momentum

in it of 32·25 lb. f.s. if falling for one sec. freely in vacuo. The mass remains the same, but the number of units of force in its weight differs at different places, if measured by a scientific unit of force, viz. a certain change of momentum in a sec.

The weight of a pound is a practical unit of force, and should never be used in calculations in which the difference in its value at Greenwich or at Quito need be taken into consideration.

The weight of one pound is sometimes called the Gravitational Unit of Force; it has this disadvantage for scientific investigations—it is not a constant force, but varies at different places on the earth's surface.

It was to meet this objection that the absolute British unit of force, *the poundal*, was introduced by Professor James Thompson; this is a scientific unit of force, which communicates unit momentum in unit time, and is consequently a constant force.

The British practical unit has this advantage, that the weight of unit mass, one pound, is the unit of force—the weight of one pound. This is the unit of force which is used in everyday life, and in mechanical and engineering work.

Units of Force.—To recapitulate: there are three units of force: the dyne, the weight of one pound, and the poundal. The numerical relation between them is as follows:—

The weight of a mass of one pound at Greenwich, being expressed in the three units of force,—1 British practical unit, *the weight of one pound* = 32·19 poundals = 445,000 dynes.

The comparison of forces measured by the different units is facilitated by the use of the scales given on p. 103.

If the weight of bodies appears in scientific investigations, the gravitational unit of force can be at once translated into scientific units. The weight of a mass of M lbs. is Mg poundals, and the weight of a mass of N gr. is Ng dynes. Continental engineers frequently use the weight of a kilogramme as a unit of force; the weight of a kilogramme is 1000g dynes, and g being nearly 1000 c.g.s., this is practically equivalent to a megadyne.

A Force of W lbs.—Sooner or later in this book, which is

intended for the use of practical people, the expression 'a force of W lbs.' must come. It is impossible to expect engineers and practical men to change their phraseology, and to speak of a pressure of '15 lbs.-weight on the square inch.' The British unit of force is a practical one, and the common expression for it is 'a force of one pound.'

In text-books on Mechanics it is now customary to speak of a 'force of 15 lbs.-weight,' but in some text-books the practice is not continued in the subjects of Heat or Hydrostatics.

It is better to face the matter at once and to impress on the reader that 'a force of W lbs.' is a common expression for a force equal to the weight of a mass, W lbs., and that it is always to be looked upon as equivalent to Wg poundals. If the matter be understood at the outset there can be no possibility of a mistake, and it is better for the expression to be explained and adopted here in explicit terms than for it to be introduced afterwards without explanation.

The expression 'a force of W lbs.' is a practical one, just as the British practical unit of force is a non-scientific unit. It is one of those expressions like 'Centrifugal Force' which have become part of the English language. If the connection between mass, acceleration, and force be thoroughly understood there need be no danger of misunderstanding in the use of such well known terms.

The Foot-Pound.—In the discussion of energy and work in the last chapter, the weight of bodies was but shortly referred to. Their weight is the force against which work has to be done when bodies are raised, and which does work when they fall. This is what is meant by saying that work is done against gravity when a heavy body is raised, and work is done by gravity when a body falls. The work done by gravity is measured by the product of the weight of the body and the vertical distance through which it has fallen; the amount of work done by or against gravity is the same whatever path the body has traversed, and whatever other forces have been applied to it.

As most of the work to be done in the world depends on gravity and the weight of bodies, energy and work could not be practically illustrated before gravity and weight had been discussed. The subject can now be resumed as a practical one.

The FOOT-POUND is the British practical unit of work done; it is the work done in lifting a mass of one pound through one foot.

Since the weight of one pound is g poundals, the foot-pound is equal to g foot-poundals, and the foot-poundal $= \frac{1}{g}$ foot-pounds.

Supposing that a mass W lbs. (or gr.) be acted upon by its weight, being allowed to fall freely, the force acting on it is Wg poundals (or dynes).

If the velocity after falling s feet be v, the kinetic energy is $\frac{1}{2}Wv^2$ foot-poundals (p. 37) $= \frac{Wv^2}{2g}$ foot-pounds. This is the work which the weight of W (Wg poundals) had done through a distance s where $v^2 = 2gs$, and it is the work which the mass can do in consequence of its velocity.

The Pile Driver.—A pile-driving 'monkey' affords an illustration of the capacity for doing work which a body has in consequence of its mass and velocity. A mass of metal is raised to a considerable height, from twelve to twenty ft. (Fig. 23); work is done on it against gravity, measured by its weight and the height through which it is raised. When at the highest point it possesses potential energy, measured in

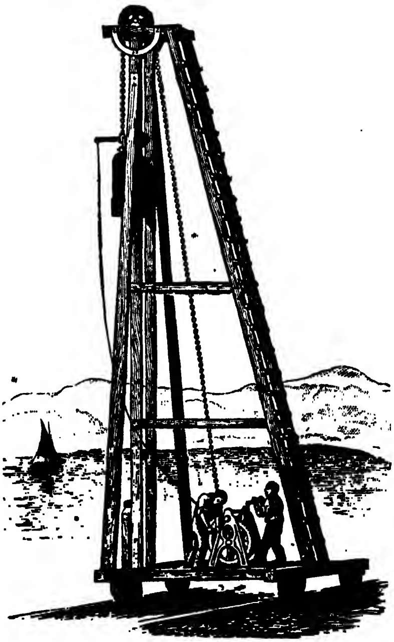


Fig. 23.—The pile driver.

the same way. It is then released and falls on the head of a pile which is to be driven into a river bed.

When the metal reaches the head of the pile it has considerable velocity; its mass combined with its velocity enable it to do work in overcoming, through a certain distance, the resistance offered to the entrance of the pile.

That the kinetic energy or capacity for doing work is due to the mass is clear, because, the greater the mass of metal that falls the greater is the movement of the pile. It also depends on the velocity, for the greater the height of fall and the greater the consequent velocity, the further will the pile be driven into the mud.

Suppose that the mass of metal be 1000 lbs., and that it be raised 16 ft., the work done against gravity is 16,000 ft.-lbs. When released the block falls 16 ft., acquiring at the end of the fall a velocity 32 f.s. ($v^2 = 2gs$; $32^2 = 2 \times 32 \times 16$); its kinetic energy is $\frac{1}{2}mv^2 (= \frac{1}{2} \times 1000 \times 32^2)$ ft.-poundals $= \frac{mv^2}{2g} (= 16{,}000)$ ft.-pounds.

Now let there be a resistance to the entrance of the pile equivalent to a force of 32,000 lbs., the kinetic energy of the moving mass enables it to work against this force by moving the pile through a certain distance. The momentum of the pile shall be neglected. The force of 32,000 lbs. ($32 \times 32{,}000$ poundals) produces in a mass of 1000 lbs. an acceleration 32^2 f.s.s. Hence the mass moving with a velocity 32 f.s. is reduced to rest in $\frac{1}{2}$ft. ($v^2 = 2as$; $32^2 = 2 \times 32^2 \times \frac{1}{2}$). The pile moves 6 inches through the mud against the force of 32,000 lbs., and the kinetic energy is transformed into 16,000 ft.-pounds of work done.

Hammers.—A very bad mistake is often made in speaking of a hammer as hitting with a 'force of so many tons.' Hammers were always used for forging until lately, and this mistake was continually being made in speaking of them: it is their momentum which measures their blow, while the effect produced by the blow, that is, the work done by it, is equal to the kinetic energy of the hammer when striking. Hydraulic forging

presses have recently been introduced which literally squeeze the metal into shape. They exert a true pressure, and may be strictly spoken of as acting with a force of so many tons weight. "Hydraulic forges or presses—for little distinction can be made between them—of 1000 to 6000 tons are becoming quite common, while a large forge capable of exerting a pressure of 10,000 tons has recently been made by an English firm. In hydraulic forging a steady and continuous pressure is exerted upon the whole ingot as it lies upon the anvil, the maximum effect being produced at its core, and so long as the press is in action the tool continues to force its way into the red-hot mass until its resistance to alteration of form equals the pressure on the ram."—*The Times.*

A hammer delivers an impulse, and if the body struck were free and elastic it would seem to move at once with a velocity depending on its own mass, and on the mass and velocity of the hammer, see Fig. 19.

But a hammer is more frequently used to overcome a great resistance. As an example, if it be required to drive a nail into a piece of hard wood, supposing that the wood were rigidly fixed and a hydraulic press used to press the nail in, a large but definite force would be required. Such a force is not usually available, so a hammer is used.

The hammer, when falling on the head of the nail, has a definite kinetic energy which enables it to do work in overcoming, through a short distance, the large resistance which the wood offers.

Now if the wood be held in a vice, as shown in Fig. 24, and a nail be driven into the part held firmly between the jaws of the vice, the blow of the hammer does not appreciably move the wood, and the nail overcomes the resistance of the wood through a short distance, till the work thus done equals the kinetic energy of the hammer.

But at the end, where the wood can bend when hit, the nail is able to move through a considerable distance without meeting with so great resistance as the wood offers to its

entrance. The kinetic energy of the hammer does work through a longer distance against this smaller resistance without making the nail enter the wood at all.

This is the reason that a carpenter places a heavy mass, *e.g.* a piece of lead, as shown in Fig. 24, behind any flimsy work into which he wishes to knock a nail. The momentum before and after impact being equal, the comparatively small mass of the hammer head imparts a small motion to the large mass.

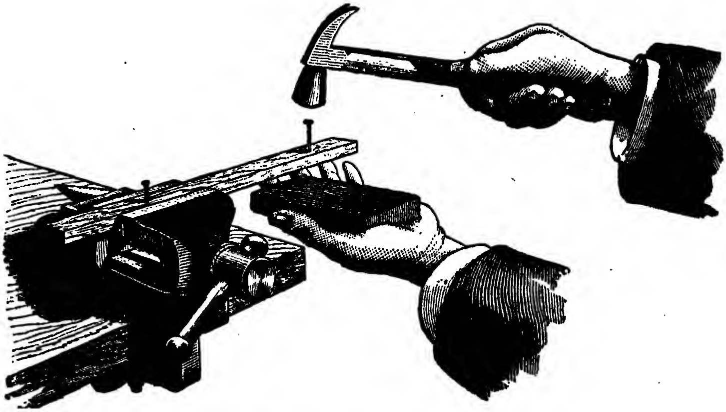


Fig. 24.—Firm and loose work.

The kinetic energy of the hammer is expended in doing work through a small distance, and therefore with great force, which is able to overcome the resistance of the wood to penetration. It is thus expended on doing useful work, instead of only bending the wood.

If the wood is very hard and rigid, the force is exerted through such a small distance that it is very great, and the nail may bend or break. 'Something must go' is an expression used of kinetic energy doing work on a rigid obstacle.

Etching on glass is done by a sand-blast. The parts not to be marked are covered with varnish, which yields a little when the sand grains impinge on it. Their kinetic energy does work

through a small distance, and therefore with a moderate force. The glass does not yield, so the force exerted is very great and causes disruption in the surface of the glass.

Power.—Power is the rate of doing work, which is an important feature in the estimation of how work is done. In the comparison of momentum and energy, it was seen that a force produces more energy when it acts for a given time on a small mass than on a large one, the reason being that the acceleration is much greater and the small mass is moved through so much greater distance in the time.

It is evident that much more effort is required to exert a given force through 500 inches in a second than to exert the same force through one inch in a second; this effort is what is called *Power.* The same force exerts a greater power when acting on a small mass than when acting on a large mass, both being free to move.

Units of Power.—The HORSE-POWER is the rate of doing 33,000 foot-pounds of work per minute.

The WATT is the rate of doing 10^7 ergs (called a Joule) of work per second.

Powers measured in the different units can be compared by means of the scales on p. 107.

Supposing that a boiler can evaporate 33 cub. ft. of steam per minute at a pressure of 3000 lbs. on the sq. ft. (about 21 lbs. per sq. in.), it is called a 3 H.P. boiler.

If in a waterfall 3000 lbs. of water fall 33 ft. every minute, 3 horse-power is running to waste.

CHAPTER V

EQUILIBRIUM

Newton's Third Law of Motion—Atwood's Machine—Morin's Apparatus—Mutual Attractions—Vertical Line—Equilibrium of Forces—Statics—Parallelogram of Forces—Triangle of Forces—Terms applied to Force—Couple—Moment of Couple—Moment of a Force—Parallel Forces—Levers—Balances—Centre of Gravity—Equilibrium: stable, neutral, unstable—Friction—Coefficients of Limiting Friction—Equilibrium and Motion—Steady Motion—Pendulum—Gyroscope—Permanence of the Axis of Rotation.

FORCE cannot be exerted unless there be some mass on which it is exerted; if force meet with equal and opposite force there is no change of motion, and the forces are said to be in equilibrium; if it meet with a force equal to part of it the remainder of the force causes a change of momentum in the body to which it is applied.

It is impossible to exert force except in meeting force opposed to it, or in causing change of momentum. Suppose, for example, a box arrived from the type-founder; it looks heavy, and I stoop to lift it, prepared to exert a force of some 50 or 60 lb. on it. But some one has, unknown to me, already unpacked it, and as I begin to lift it I find that a force of some 2 or 3 lb. suffices to overcome its weight; I do not exert the 50 or 60 lb. which I was beginning to put forth, while the force which I do apply, being much too great, causes a rapid acceleration to the box and some surprise to myself.

Such facts as this lead to **Newton's Third Law of Motion.**

Action and reaction are equal and opposite.

If two unequal masses, A of a lbs. and B of b lbs. (b being less than a) are joined by a smooth and flexible cord passing over a pulley (Fig. 25), the weight of A [$a \cdot g$ poundals] is met by a force exerted by the weight of B [$b \cdot g$ poundals] through the string; $(a-b) \cdot g$ poundals is the resultant force, which causes an acceleration in $(a+b)$ lbs., the combined mass of A and B.

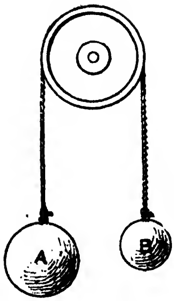


Fig. 25.—Two unequal weights.

The *action* of the larger force, $a \cdot g$ poundals, is met by an equal and opposite *reaction*, consisting of (i.) a force $b \cdot g$ poundals, exerted by the weight of B through the string, and (ii.) a rate of change of momentum caused by $(a-b) \cdot g$ poundals. This is the principle of Atwood's machine.

Atwood's machine and Morin's apparatus are used to calculate the value of g and to test experimentally the laws of falling bodies.

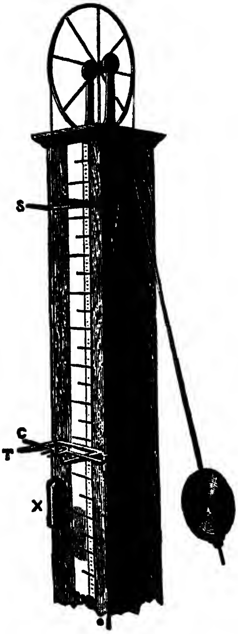


Fig. 26.—Atwood's machine.

In **Atwood's Machine** two equal masses X are suspended by a fine string over a very light pulley, running easily on ball bearings (Fig. 26). A small mass or '*rider*' C is placed on one of them, and motion follows, with an acceleration caused by the weight of the 'rider' acting on the masses in motion. This problem has just been discussed and illustrated in Fig. 25, when the acceleration is $\frac{a-b}{a+b} \times g$. f.s.s. If the difference between a and b, which is the mass of the rider, be small compared with A + B, this acceleration is small, and the velocity attained is easily measured. The rider C is placed on the mass X by the fall of its support S, detached at a moment regulated by the pendulum, and the rider is removed from X by the

support T at a fixed distance below. The interval of time taken between the supports is observed, and the velocity of the mass at T ascertained by observing the motion after the rider is left there. In this way the formulæ of Kinematics $v^2 = 2gs$, $s = \frac{1}{2}gt^2$, etc., may be experimentally verified and the value of g approximately determined. But the friction of the cord and wheels cannot easily be allowed for, and they affect these values.

In **Morin's Apparatus** a long cylinder is made to revolve on a vertical axis uniformly by clockwork (Fig. 27). It is covered with sectional paper; the equal horizontal distances represent equal times, and the vertical distances the space described by a falling body. When the cylinder is running uniformly a heavy mass of lead is allowed to fall so near to it that a pencil carried by the lead draws a line on the paper.

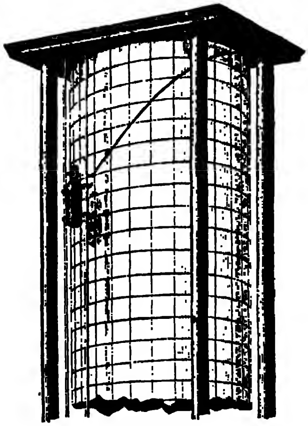


Fig. 27.—Morin's apparatus.

If the cylinder were at rest this line would be vertical. If the motion of the lead were uniform the line would be a spiral, or if the paper were unrolled a diagonal straight line. But when the weight falls freely the line traced is a parabola.

Rev. J. B. Lock suggests the adaptation of Atwood's two weights (Fig. 25) to Morin's vertical moving cylinder, as the cylinder cannot be long enough for a free fall of more than one second in duration.

Mutual Attractions are equal and opposite.

It was remarked at the beginning of the last chapter that Newton's observations led him to conclude that all bodies attract one another. But the mass of objects on the earth's surface is so insignificant when compared with the mass of the earth that the acceleration produced in them by this force of attraction is

great, while the acceleration produced in the mass of the earth is insignificant, and cannot be detected.

The effects of mutual attraction can be seen in the motions of the sun, earth, and moon. Considering first the earth and moon alone, the earth's mass is about eighty times that of the moon, while the moon's distance is about sixty times the earth's radius.

Now, if the two balls in Fig. 14 (p. 27) be made in these proportions they will illustrate the motion of earth and moon. When they are rotated the metal connection between them exerts an equal force on both. They rotate about a point which divides the line between their centres in the ratio of their masses, consequently the rotation takes place about a point inside the larger one which represents the earth; this globe would wobble, and the moon perform an orbit round it. This experiment may help to show how the moon can truly be said to perform an orbit round the earth, though it attracts the earth with a force equal to the earth's attraction on it.

In the same way, considering the earth and moon as one mass, attracting and being attracted by the sun, the sun's mass is about 325,000 times that of the earth, while the sun's distance from the earth is about 215 times the sun's radius. If the balls were made to this proportion, the sun would hardly be seen to wobble at all, so near to its centre would be the point about which rotation takes place. Hence, though the earth attracts the sun with a force equal to that with which the sun attracts the earth, the earth and moon perform an orbit about a point which is nearly the centre of the sun.

The moon's attraction on the earth is made evident in the movement of the tides; the water is free to move, and its mass is small compared to the mass of the moon.

In every part of nature, action and reaction are equal and opposite.

Vertical Line.—The plumb-line (Fig. 28) is a cord, at the end of which is a ball of lead. The direction of the earth's attraction on the lead is towards the centre of the earth, so when the lead is hanging at rest the string exerts on it a force

equal and opposite in direction to the force of the earth's attraction on the lead. The line drawn through the centre of the earth and any point on its surface is called a 'vertical line'; as it is in this direction that the lead is attracted it is in this direction that the string must hang to support it. The result is that a plumb-line always gives a vertical line, and it is used by the mason and the carpenter as a guide in building.

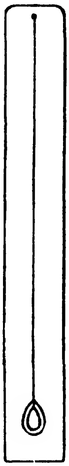


Fig. 28.—The plumb line.

Equilibrium of Forces.—Equilibrium exists when force is opposed by other force exactly equal to it, so that no change of momentum is caused. If a heavy stone be carried in the hand the muscles are called upon to exert a 'reaction' equal and opposite to the 'action' of the weight of the stone. A letter resting on a letter weigher presses on and is pressed by the letter weigher with equal forces; two railway buffers are pressed equally when the screw couplings are tight.

In these cases the forces are said to be *in equilibrium.*

Statics is that branch of Dynamics which deals with forces in equilibrium which are applied to a body at rest.

i. *Equilibrium of Forces Applied at a Point and in one Straight Line.*—In a 'tug of war' a rope is pulled by two contending parties until a mark in the middle of it is drawn over a line. If the parties are evenly matched, it may happen that for some minutes the rope does not move at all, although each party be doing their best to pull the other over. Any point in the middle of the rope is then subjected to two equal forces in opposite directions, and the forces at that point are in equilibrium. The sum of the forces exerted by the competitors in one direction is equal to the sum of those in the opposite direction. If one side exert a greater force than the other it must produce momentum in the whole mass of rope and competitors.

Forces applied at a point and in the same straight line are in equilibrium so long as the sum of those in one direction is equal to the sum of those in the opposite direction.

ii. *Of Forces not in one Straight Line.*—On page 33 it was observed that the resultant of two forces applied at a point is represented in magnitude and direction by the diagonal through the point of the parallelogram, of which adjacent sides represent the forces.

If two horses are attached by chains to a tree stump, and are set to pull it out of the ground, their combined force is opposed by the resistance of the stump, which exerts a force equal to the resultant of their forces, and in the opposite direction. It must be observed that the horses cannot pull unless a resistance is opposed equal to the resultant of the forces which they exert. Until they move the horses can only exert force to the extent of the resistance of the stump, and any force which they exert beyond that amount will cause the stump to move. The resultant of two forces is not exerted unless it be met by equal and opposite force, or produce momentum.

When three or more forces applied at a point are in equilibrium, each of them is equal and opposite to the resultant of the others.

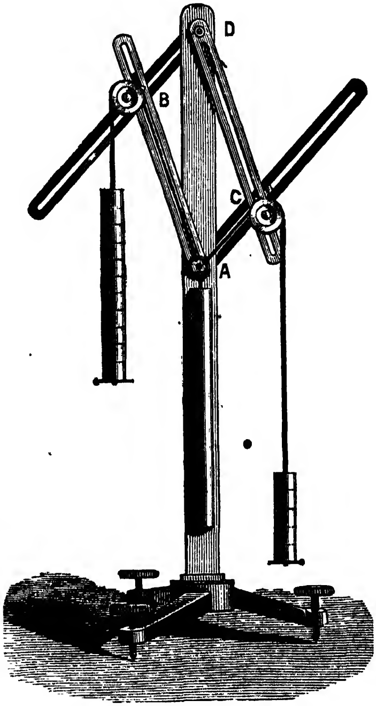


Fig. 29.—Parallelogram of forces.

Parallelogram of Forces. The apparatus shown in Fig. 29 is designed for experimental illustration of the parallelogram of forces. The four arms pivot about the points A and D, and they can be clamped at B and C in any position; cords pass round pulleys running easily on ball bearings at B and C, and are fastened to a ring at A. Weights

are suspended from these cords, and it adds to the graphic illustration of the principle for them to be made of uniform diameter (about 3 inches), so that their weight varies as their length.

The system of weights is in equilibrium provided that ABCD is a parallelogram, and the weights hanging from A, C, and B are equal in length to AD, AC, and AB.

Triangle of Forces.—The three weights hanging at A, B and C are proportional to the three sides of the triangle DA, AC, and CD; they also exert forces in the direction of those sides taken in order, that is to say, in the directions D to A, A to C, and C to D. Hence experiments with this apparatus also illustrate the principle known as THE TRIANGLE OF FORCES.

Three forces applied at a point are in equilibrium when they are represented in magnitude and direction by the sides of a triangle taken in order.

Terms applied to Force.—Various terms are applied to forces, according to the particular manner in which they tend to transform energy.

Attraction or *Repulsion* are forces which two bodies exert on one another at a distance.

The *Weight* of a body is the force of attraction between it and the earth.

Stress, in the most general sense, is the force mutually exerted by two bodies on one another, and in this sense it includes attraction and repulsion, whether gravitational, magnetic, or electric. In the ordinary sense of the word—

A Stress tends to change the form or bulk of a body.

A Strain is a change of form or bulk; stresses are named according to the nature of the strain which they tend to produce, and are measured by the force per unit of area which is exerted.

Compressive Stress is the force per unit of area tending to compress.

Tensile Stress is the force per unit of area tending to elongate.

Shearing Stress is the force per unit of area tending to produce distortion.

A Shear is simple distortion, such as the deformation of a circle into an ellipse of the same area, or the sliding of one layer over another so as to deform a square into a parallelogram of equal area.

'Pressure,' in the strict sense of the word, is compressive stress, and 'tension' is tensile stress; but in the more usual sense of the words they are forces considered as applied at a point. In this sense—

Pressure is the force which one body exerts on another when it is in contact with but not necessarily fastened to it.

Tension is the force exerted by a string or other connection which prevents bodies from separating.

All forces are measured in terms of units of force, discussed on p. 49.

Couple.—Two equal and opposite parallel forces applied to a body are called a *couple;* they tend to turn it round an axis perpendicular to the plane containing them.

Moment of Couple.—The amount of the tendency which a couple has to turn a body round an axis is doubled if the forces are doubled; also it is doubled if, the forces remaining the same, the 'arm' or distance between them is doubled. Hence the turning tendency, or moment, varies as the product of one of the forces into the perpendicular distance between them.

Couples are continually exerted in practice, for example, by a screw-driver, a watch key, a milled head of a screw, or a capstan. The effect of a couple is frequently seen when one point of a body is fixed; a force applied at another point causes a parallel, equal and opposite pressure on the point. This couple tends to turn the body round an axis throughout the point.

Moment of a Force is the measure of the tendency which it has to turn a body round an axis.

If the rigid body represented in Fig. 30 be free to move about a point A, and a force P be applied to it, A not being in its line

of action, a force appears parallel, equal and opposite to P, and acting through A; this couple has a moment AM × P. The moment of the force P as tending to turn the body round A is measured by the product of the force into the length of the perpendicular AM let fall from A on the direction of the force.

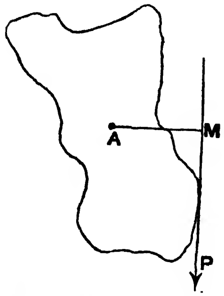


Fig. 30.—Moment of a force.

This is called the moment of the force P about A, and its measure is AM × P.

Parallel Forces.—Two parallel forces applied to a rigid body cannot be in equilibrium; but equilibrium may be restored by applying a third force at a point either rigidly connected with or part of the body. In the experiment shown in Fig. 31 XY is a straight bar, which is suspended at the middle point C from a support. The bar rests horizontally and turns freely about C, and should be supported by a spring-balance or by a cord passing over a wheel and weighted. The weights of bodies placed at A and B are parallel forces, and the bar is a rigid connection between their points of application. A third force is applied at C; the first condition of equilibrium is that this must be equal and opposite to the other two forces. Also when the bar is in equilibrium, the moment of any two of them tending to turn the bar round a point must be balanced by the moment of the third force about that point. If the force P applied at A be the

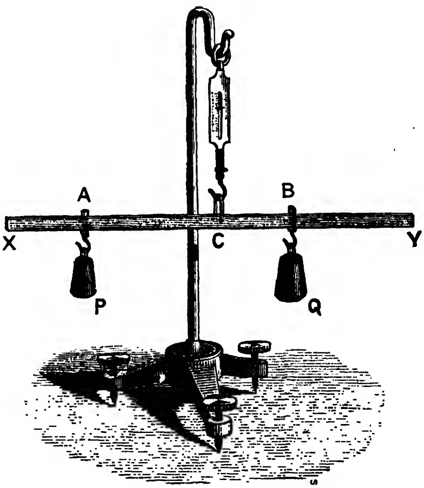


Fig. 31.—Parallel forces.

weight of 3 lbs. and Q at B of 6 lbs., the reading of the balance is 9 lbs., the weight of the bar being first allowed for. The distances of the points A and B from C depend on the magnitude of P and Q; P tends to turn the bar round C in a direction opposite to the hands of a clock, with a moment measured by $P \times CA$, Q tends to turn the bar with the clock hands, with a moment $Q \times CB$: these moments must be equal if the bar is in equilibrium, $P \times CA$ must equal $Q \times CB$, P and Q being 3 and 6 lbs., let CB be $5\frac{1}{2}$ in., then CA is 11 in., $3 \times 11 = 33 = 6 \times 5\frac{1}{2}$.

In the same way the moments of the forces about any other point must be equal; about A for example. The force applied at C (P + Q or 9 lbs.) tends to turn the rod *anticlockways* about A; the moment of Q. 6 lbs., is *clockways*. As the rod is in equilibrium, the moment of these forces about A must be equal and opposite, which the experiment shows to be true,

$$\text{For } P+Q \times CA = 9 \times 11 = 99 = 6 \times 16\tfrac{1}{2} = Q \times AB.$$

Levers.—A *Lever* is a rigid rod which is free to turn about some fixed point in it. The fixed point about which a lever is free to turn is called the *fulcrum*.

In the experiments made on parallel forces with the apparatus (Fig. 31) the principle of the lever is illustrated. The rod is a lever; the forces applied to any lever when in equilibrium and their points of application are connected as shown in those experiments.

The forces at the ends must be in the same direction, the force in the middle in the opposite direction and equal to their sum. To ensure equilibrium in the lever, the moments of the forces which tend to turn it about any point in one direction must be equal to those tending to turn it in the opposite direction.

The simplest form of a lever in equilibrium is the common balance, in which the two arms are equal and they are horizontal when the weights in the scale pans are equal.

The common balance is arranged with different proportions to effect different purposes.

A Shop Balance for weighing goods for sale should be made as Fig. 32, with the weight of the beam below the point of suspension, so that it will soon come to rest horizontally when the weights in the two arms are equal. This is called a '*stable*' form of balance.

A Chemical Balance, long arm (Fig. 33), is used in measurements of great delicacy. It should detect a very small difference of the weights in the two arms; this form is called '*sensitive*.'

The friction at the point of suspension must be very small;

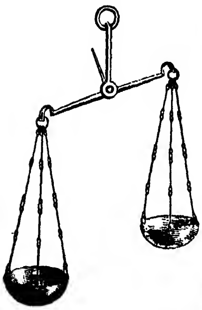


Fig. 32.
Shop balance.

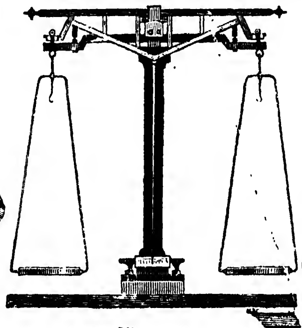


Fig. 33.
Chemical balance (long arm).

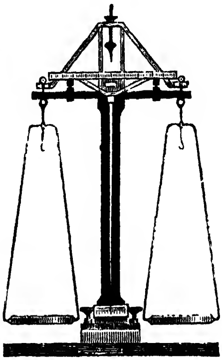


Fig. 34.
Chemical balance (short arm).

it is usually a steel knife-edge. The weight of the beam is not much below the point of suspension. The arms are long, so that a small difference of the weights in the two scales may give a perceptible moment about the fixed point.

A Chemical Balance, short arm (Fig. 34).—Bunge of Hamburg has introduced chemical balances of short beam but highly sensitive. The advantage of this plan is that the time of oscillation is much less, and the weighing can be done more quickly. The long vertical index shows when the beam swings evenly about the horizontal without waiting for rest.

Another kind of balance, the steelyard, has not equal arms, and the forces at the ends are not equal. This is much used by

butchers in two forms: (i.) the *Common* or *Roman Steelyard* (Fig. 35). In this a heavy ball is moved on the long arm of a lever until its weight at B is in equilibrium with the weight of the meat suspended on the short arm at A, and the lever is horizontal. The lever is so arranged that it rests horizontally without any weights.

(ii.) The *Danish Steelyard* (Fig. 36).—Here the fulcrum C is moved until the weighted end of the steelyard A and the weight of the joint at B are in equilibrium and the lever is horizontal.

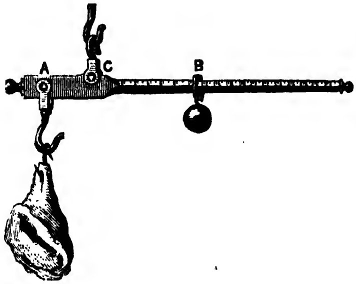


Fig. 35.—Roman steelyard.

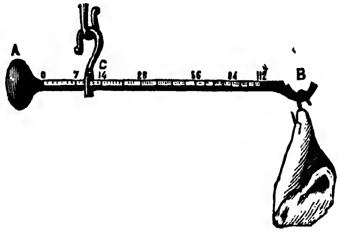


Fig. 36.—Danish steelyard.

In both steelyards the position of the graduations depends on the weights of the iron lever and the movable masses.

Balances afford examples of parallel forces in equilibrium; and of levers as treated in statics. But in practice levers are usually employed to do work, and their further consideration is deferred to the next chapter.

Centre of Gravity.—The earth attracts every particle of a body, exerting a number of parallel forces, whose sum is the weight of the body. The centre of these parallel forces, through which the forces act, however the body be turned about, is called the 'centre of gravity' of the body. The simplest case is that of a sphere; it is obvious that the mass of a ball is so evenly disposed about the centre that the ball would be in equilibrium if a force vertically upward and equal to its weight were applied at its centre. This is equally true of that point in

every body about which the mass is evenly disposed. Let a flat board (Fig. 37) be suspended from a point *a*, a plumb-line being also suspended from the same point; if the vertical line *ab* thus given be traced on the board the mass must be evenly disposed about this line, or the board would sink on that side to which the moment of its weight inclined it. Similarly, if the board and plumb-line be suspended from another point *c*, and the vertical line *cd* be also traced on the board, the mass of the board must be evenly distributed about this line also.

It follows that where these lines intersect there must be in the middle of the thickness of the board a point G about which

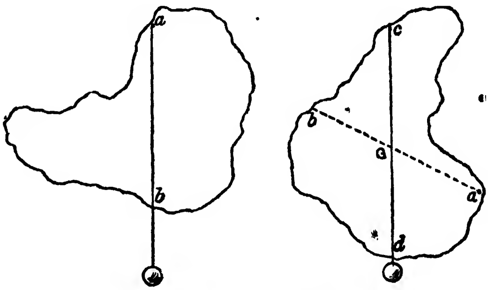


Fig. 37.—C.G. of flat board.

the moment of the weight is evenly balanced; this point is called *the Centre of Gravity* or *Centre of Mass.*

The centre of gravity may actually be out of the body itself; for example, in the case of a ring like a curtain ring, the centre of gravity is evidently in the centre, which is not in the substance of the ring.

In all cases where it is possible to suspend the body at the centre of gravity the body will rest in any position when so supported, for the mass of the body being evenly distributed about this point its weight will not have a tendency to turn the body in one direction more than in another. Also if a body be suspended on an axis which passes through the centre of gravity it will rest in any position in which it is placed.

Equilibrium of Position.—A body rests in equilibrium when its centre of gravity is supported by a connection with a fixed point in the vertical line through the c.g. If a ball hang by a string it is in equilibrium, and also if a stick be balanced on the hand (Fig. 38) it is in equilibrium.

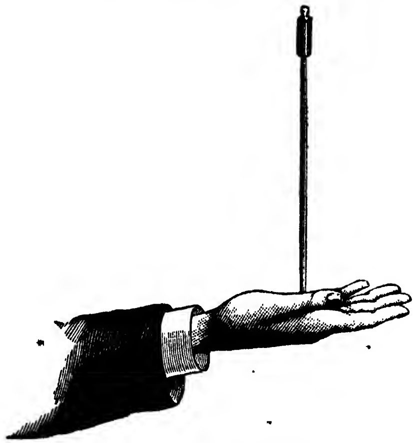


Fig. 38.—Unstable equilibrium.

There is evidently a great difference between these two cases. In both the centre of gravity is supported, but in the latter the least movement will cause the stick to tumble over, while in the former if the ball be displaced it will tend to return to its former position. The ball on the string is said to be in *stable* equilibrium; the stick on the hand in *unstable* equilibrium.

A ball and a roller are said to be in *neutral* equilibrium on a horizontal plane, for neither have a tendency to return to the former position when displaced, as is the case in stable equilibrium exemplified in the ball and string.

Stable equilibrium is ensured when the centre of gravity of a body is either under the point of support, or when a vertical line from the centre of gravity passes between the outside limits of the base on which the body rests. In these cases the centre of gravity rises when the body is displaced; in unstable equilibrium the centre of gravity falls when the body is moved; in neutral equilibrium the centre of gravity remains at the same height. An egg affords an example of each of the three forms of equilibrium—neutral when on its side and rolled, stable when on its side and rocked, unstable when balanced on its end.

An experimental illustration of this can be shown with blocks of wood (Fig. 39). The first has its centre of gravity at

A, and is in stable equilibrium; the second, with its centre of gravity at B, is attached to A, and the centre of gravity of the two combined is at C, the vertical line drawn through C falls on the edge of the base, so that the whole is in unstable equilibrium; if the blocks be at all disturbed they will fall. If another block be placed on the top having its centre of gravity at D, it brings the centre of gravity of the whole system to B; then the vertical line through the centre of gravity falls outside the base of support, and the system will not stand. If, however, a block of lead be added at X so as to bring the centre of

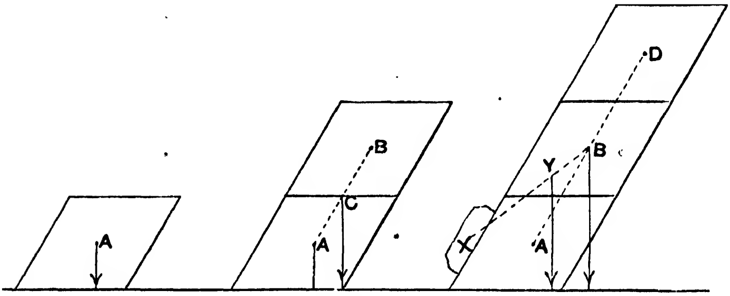


Fig. 39.—Equilibrium of position.

gravity of the whole to a point Y between X and B, which is over the base of support, the whole system will stand in stable equilibrium, though it looks so top-heavy.

The leaning tower of Pisa is often instanced as a case of stable equilibrium. It is a beautiful piece of architecture, but the mind is rather concerned with the cohesion of materials and the unnatural appearance of a leaning tower than with the question of its being top-heavy. In fact, if the materials are sufficiently strong, there is no reason why a really top-heavy tower should not be built, so long as the cement and stone will cling together and hold it down to the foundation.

Friction is the force which is called into action when any force tends to move a rough body over a rough surface. When one body rests on another each exerts an equal pressure on the other, normal to their surfaces. So long as the weight of the

body or any force applied to it is in the direction of the normal neither has any tendency to move over the other, and there is no friction. But when any force is applied to the body in another direction the component of the force parallel to the surface tends to make one body move over the other; friction is then called into action—a force equal and opposite to this component, and equilibrium is maintained.

But there is a limit to this force called *Limiting Friction*, which is the greatest friction possible for that pressure between those surfaces. It is called into action just before motion takes place.

For example, a mass of 20 lbs. rests on a plane inclined to the horizontal at an angle of 30° (Fig. 40); if the plane were smooth the body would slide down, but friction supplies a force along the plane which maintains equilibrium. In the diagram the sides of the triangle of forces A B C represent in magnitude and direction the forces which are applied to the body, and are in equilibrium, viz. the weight, the pressure of the plane, and the friction, represented by AB, CA, and BC. In the present example BC is half of AB; the friction is a force of 10 lbs.

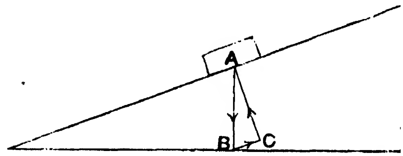


Fig. 40.—Equilibrium due to friction.

It is assumed here that the substances are such that the weight will not slide down the plane when it is inclined to the horizon at 30°, but the greatest inclination of a plane on which a body will rest depends on the materials of the body and the plane. For every pair of substances there is an angle, which is the greatest at which a plane of one substance can be inclined to the horizontal, so that a body of the other substance will not slide down it. This is called the *Angle of Friction;* the ratio of the friction to the pressure, *i.e.* BC/CA, is called the *Coefficient of Friction.* It is the tangent of the angle of friction.

To calculate the Angle of Friction for various substances. A plane is provided whose inclination to the horizon can be varied gradually, and plates of different substances to cover it (Fig. 41).

A weighted box rests on the plane, plates of different substances being fastened to its lower surface. The plane is slowly inclined, and its inclination to the horizontal, when the box begins to move, is noted; this is the angle of friction for the pair of substances under observation. The experiment is repeated several times for each pair, and the mean is taken.

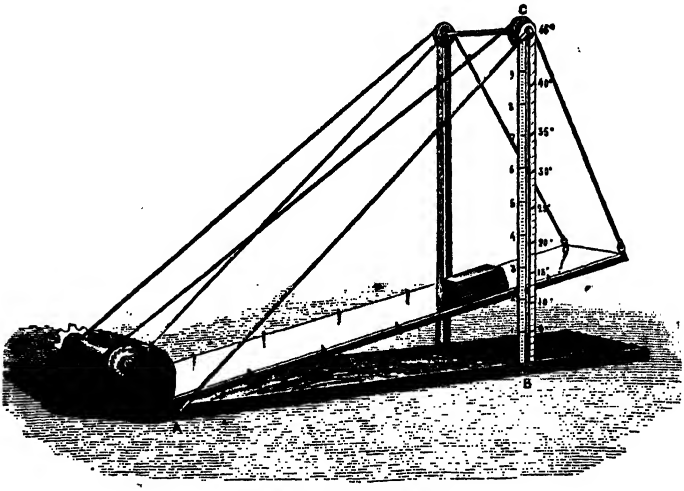


Fig. 41.—Friction apparatus.

The following table contains the results obtained in experiments on different substances:—

Coefficients of Limiting or Statical Friction (Morin).

Substances.	Angle of Friction, ϕ.	Coefficient μ or tan ϕ.
Oak on oak	31°·50′	·62
Elm on oak	34°·40′	·69
Cast-iron on oak	33°·0′	·65
Leather on wood	25°·30′	·47
Leather on cast-iron	28°·30′	·54
Wrought-iron on cast-iron	10°·45′	·19
Cast-iron on cast-iron	9°·5′	·16
Brick on stone	33°·50′	·67

It is understood that the substances are planed and smoothed as much as possible.

Laws of Friction.—Experiments with the apparatus just described illustrate the following laws of limiting friction :—

i. The angle of friction remains the same for all weights so long as the natures of the surfaces remain the same.

ii. The angle of friction remains the same whatever the size or shape of the surfaces.

When once the box has begun to move it descends the plane with increasing velocity.

The friction of the surfaces just before moving is in equilibrium with the component of the weight along the plane. When the body has begun to move the component of the weight causes acceleration, showing that the moving friction is no longer equal to it, but less than the limiting friction.

As this chapter treats of equilibrium, and mainly deals with statics, *i.e.* with bodies at rest, the discussion of moving friction must be deferred to the next chapter.

The coefficients of statical friction are of great importance in many instances. Leather belting is used to drive machinery by its limiting friction on metal or wooden pulleys; belting should not shift on the pulleys.

The driving wheels of locomotives when running should not slip on the rails. There is a weight of 16 tons on the driving wheels of a G. N. R. express engine. Taking the coefficient at ·16, the greatest force of traction the engine can exert is 2·56 tons.

Our being able to walk depends on the friction between the shoe and the pavement being less than limiting friction. A comparison of the coefficients will show why leather is used and why shoes with nails in them are dangerous on cast-iron foot-plates. On reflection it will be seen that we are continually relying on statical friction in ordinary life.

Equilibrium and Motion.—A body may be in equilibrium though it be not at rest. When a locomotive is drawing a train with uniform speed, its drawbar is in equilibrium; the tractive force of the engine is equal to the resisting forces in the

train. A steamer moving with uniform speed in smooth water is in equilibrium, the enormous force exerted on it by the screw shaft meets with equal and opposite force in the resistance of the water.

Steady Motion.—If forces applied to a body in motion are not in equilibrium, their resultant imparts acceleration. In a large number of cases, this acceleration is alternately positive and negative, and an exchange continually takes place between the potential and kinetic energies, as was seen in the motion of a pendulum (p. 41); this is called *Oscillation.*

In other cases the velocity is such that the acceleration carries the body round in a curve called an *Orbit.* Such motions are stable and have the element of permanence; and motion in an orbit or in oscillation is called Steady Motion.

Laws of Pendulums.—A ball suspended by a string represents 'a simple pendulum.' When at rest it hangs vertically; when displaced it oscillates, and if there were no friction would continue to swing. The pendulum is in steady motion.

i. *Length.*—If three pendulums (A, B, and C, Fig. 42) be arranged so that while A swings once, B swings twice and C three times, their lengths are found to be as the numbers 1, 4, and 9. The time of a complete swing is proportional to the square root of the length.

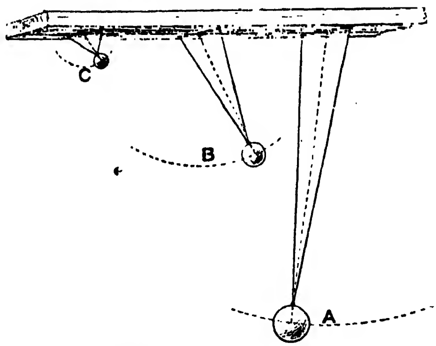


Fig. 42.—Laws of pendulums.

ii. *Value of g.*—The same pendulum on a larger planet would swing more quickly, for the ball would be more powerfully attracted. The time of the swing is less when the attractive force is greater, and so the time of the oscillation of the same pendulum may be used to determine the value of g at different places.

These two facts are combined in the expression $t = 2\pi\sqrt{\frac{l}{g}}$ where t sec. is the time of a complete swing of a pendulum l ft. or cm. in length.

iii. *Pendulum as Standard Length.*—As the time of oscillation depends on the length of the pendulum and on the value of g, it follows that a pendulum swinging in unit time, at a certain place, gives a standard of length. An Act of Parliament 5 Geo. IV. defines the yard to contain 36 such parts, of which there are 39·1393 in the length of a pendulum vibrating seconds in vacuo in the latitude of London. When the standard measures were destroyed by fire in 1834 this method of ascertaining the standard was not found to be sufficiently accurate, and the yard is now defined by the length of a bronze bar (see p. 6).

iv. *Isochronism.*—Galileo's attention was attracted by the motion of a swinging lamp in the Cathedral of Pisa. He noticed the even time of its oscillations, and concluded that however long or short the path of a pendulum the time of its swing is the same. This conclusion is correct if the arc described be small.

In Fig. 42 the pendulums are shown supported by two strings. This makes them swing in one plane; but 'the length of the pendulum' is the radius of the swing, not the length of the strings.

Conical Pendulum.—If a simple pendulum be displaced to A (Fig. 43), and then be projected perpendicularly to the plane CAA; the ball will describe a horizontal circle AA_1A, and the string will describe a cone.

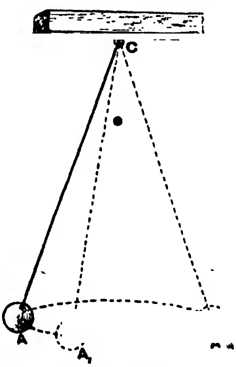


Fig. 43.—Conical pendulum.

This is another form of steady motion, and the motion of the ball resembles that of the heavenly bodies in their orbits.

Bodies acted upon by forces from a distance are in equilibrium when they oscillate about a position of equilibrium. The heavenly bodies do not perform their orbits in regular

curves, but every part of their motion oscillates about the mean value.

Gyroscope.—Foucault's experiments with the Gyroscope (Fig. 44) afford examples of steady motion.

Fig. 44.—Gyroscope.

This instrument consists of a wheel A, with a heavy rim like a top, which turns very freely on its axis, and has its centre of gravity exactly in the middle of a ring. This ring is free to move in any way, being on the pivots B, B, and the fork which supports B, B turning freely on a pin at C. The wheel A is in neutral equilibrium in all positions.

1. If the wheel be at rest and the base be turned slowly about in any way, the ring and wheel are turned also. But if the wheel be rapidly spun round by means of a cord wound round it, the axis maintains its direction in space, and is not diverted by movements of the base. Suppose that the axis be pointed towards the sun or a star, it will continue to point in that direction 'as if it had a will of its own,' however the base may be turned about.

This shows that the direction of the axis of rotation of a rapidly revolving body is a state of rest or uniform motion which is only altered by force.

2. If the wheel be swiftly rotated and the ring B, B be detached and suspended horizontally by a string fastened to it at D, the ring does not fall but remains horizontal, and slowly revolves round the string as an axis.

3. If the wheel when spinning rapidly be detached from the ring B, B, and allowed to spin with one end supported, the

axis performs a gyration round the vertical through the support after the manner of a top.

The earth's axis has a motion like this which causes the precession of the equinoxes; the axis makes one complete gyration in 25,868 years.

Both of these last experiments exhibit steady motion, and the same explanation applies to both. The disc with a heavy ring is in rapid motion about the axis OD in the direction of the arrow *a* (Fig. 45). Now if the disc were at rest and suspended at D its weight would cause it to fall, that is to turn about an axis OB as the arrow *b*.

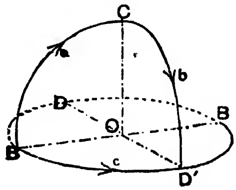


Fig. 45.—Gyration, two rotations combined.

This slow motion *b*, combined with part of the rapid motion *a*, causes a slow motion about an axis OC as *c*. This is the gyration observed.

4. That this is the explanation is cleverly shown by Foucault in another experiment. The gyroscope being suspended, as shown in the engraving (Fig. 44), on its gimbals in perfect equilibrium, it is rotated rapidly in the direction of clock-hands as *a* (Fig. 45). If a small weight be hung on to the end of the axis opposite to D nearest to the spectator, tending to cause the motion described by *b*, the whole will perform a slow gyration in the direction *c*. But if the weight be hung on to it at D, this gyration will be reversed, since the weight so hung would cause the wheel to incline in the opposite direction to *b* if it were at rest.

Permanence of the Axis of Rotation.—The observations made with the gyroscope have shown that not only does the motion of a uniform body about its axis continue uniform, but the direction of its axis remains the same unless it be altered by force.

This must be considered as part of the first law of motion, as described in Chap. I.

Rate of motion about an axis as well as the direction of the

axis must be considered in the description of 'the state of rest or motion.' Momentum, whether linear or angular, remains unaltered except by force.

A very large and well-constructed gyroscope can be used to show the diurnal motion of the earth; the axis continues to point to a star or the sun, so that it changes its direction with reference to surrounding objects, which revolve with the earth.

If a heavy pendulum with a long string be set in motion with great care, so as to oscillate in the plane through the point of support and a celestial object, the pendulum will continue to oscillate in a plane passing through that object, and will therefore alter its line of oscillation relative to the earth. Both these experiments are due to Foucault.

In the latter case it is the permanence of direction of linear momentum, in the former that of angular momentum which is utilised to show the earth's diurnal motion.

These experiments show that momentum is permanent in direction, and does not change with terrestrial surroundings. The question is often discussed whether this direction is absolute, or with reference to what objects it is fixed.

As a matter of experiment the utmost that can be shown is that the direction of a motion or of an axis of rotation points for a short time towards a star, but the experiments show that the more interferences to free motion are removed the more permanent is the direction of momentum. Hence they would seem to show that, if a body could be isolated from all forces, its momentum would be absolutely unchanged.

CHAPTER VI

MACHINES

Machines—Efficiency of a Machine—Perfect Machine—Mechanical Advantage—Levers—Wheel and Axle—Differential Wheel and Axle—Inclined Plane—Wedge—Screw—Pulleys—Moving Friction—Rolling Friction.

Machines are contrivances by means of which a force applied at one point is exerted at another in changed conditions of magnitude, direction, or distance.

There are certain limitations to the capacity of living animals to do work. Work is the exertion of a force through a distance in its own direction. Now a man or a horse can only exert a moderate force, but can exert it continuously for some time or through some considerable distance. A machine may be used to convert work done by an agent exerting a small force through a long distance into work done by the machine through a small distance but with great force. Suppose, for example, that a block of stone of some tons is to be lifted, while a man unaided cannot exert a force of more than 100 lb. If the stone weigh 10,000 lb. and has to be raised 1 ft., 10,000 ft.-lb. of work are required; now the man can exert a force of 100 lb. through 100 ft., but could not exert 10,000 lb. through ever so short a distance, so he uses a machine to convert work done by his small force through a great distance into a large force exerted through a short distance.

On the other hand, it may be that it is requisite to exert a small force only, but to exert it rapidly through a long distance,

while it is more convenient for an animal or a steam-engine to exert a larger force through a less distance. In a spinning wheel the bobbin runs round at a more rapid pace than any human arm could turn it, but with a small force, and this is effected by a machine.

No work is gained by using a machine. In fact work is 'lost'; there is friction between the parts, and so useless work is done; cords are stiff, the air resists motion, and in many ways the efficiency of a machine is impaired by the resistance of its parts.

The efficiency of a machine is the ratio of work done by the machine to the work done on the machine.

For the elementary study of machines it is necessary to imagine a **perfect machine**, in which wheels and surfaces are perfectly smooth, cords perfectly flexible, and the air does not impede motion. The efficiency of a perfect machine is unity; the work done *on* the machine is equal to the work done *by* the machine, and this is called the **Principle of Work**, stated thus:—If a force P be applied to a machine through a small distance r, and the machine exert a force Q through a small distance s, then, in a perfect machine, $P \times r = Q \times s$.

Various simple machines will now be described as illustrations of the *Principle of Work.*

Mechanical advantage is the ratio of the force exerted by the machine to the force applied to the machine. If the force exerted by the machine is greater than the force applied to the machine, it is exerted through a smaller distance; and *vice versâ*, if the mechanical advantage is less than unity the force is exerted by the machine through a longer distance. This is expressed by saying that 'what is gained in force is lost in distance.'

Levers.—Levers have been already referred to in order to explain the equilibrium of parallel forces. They will be shortly referred to again as examples of machines for doing work in a way more convenient to the agent. The lever is the simplest form of machine, and as the principle of the lever in equilibrium has been studied already it can be used to prove the *principle of work, i.e.* that the work done on the machine is equal to the

work done by the machine. Suppose that a lever AB is in equilibrium under the three forces P, Q, and P + Q (Fig. 46). Let the smaller force P be exerted by the agent, and move the end A through a small distance r, the fulcrum being at C; then the force Q will be exerted by the lever through the small distance s through which B moves, and the lever thus does work $Q \times s$.

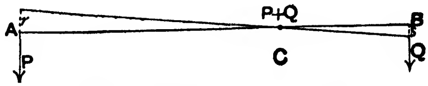


Fig. 46.—Principle of work proved.

In the last chapter it was shown experimentally that $P \times AC$

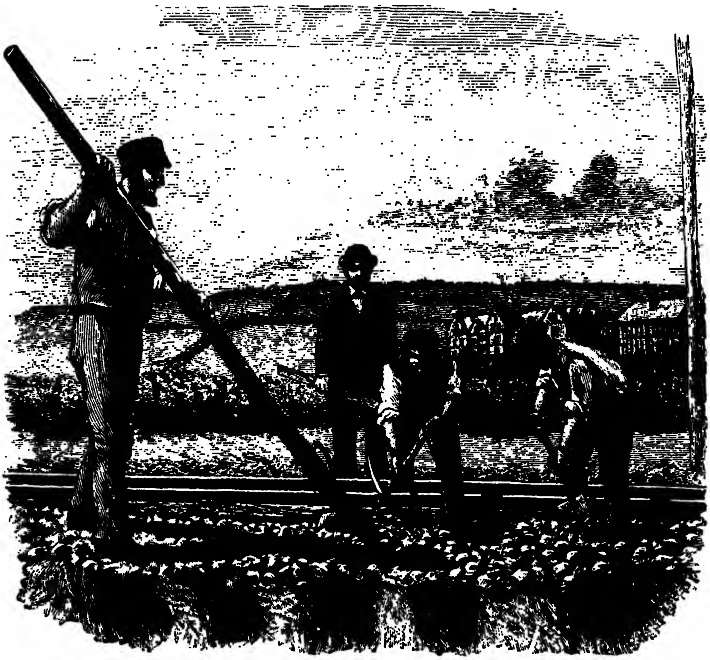


Fig. 47.—Railway-men's lever.

$= Q \times BC$; and since r bears the same ratio to AC that s does to BC, it follows that $P \times r$, the work done *on* the lever, must be

equal to Q × *s*, the work done *by* the lever (*the Principle of Work*).

P is here less than Q, so that it has to be exerted through a greater distance than Q is moved.

In other cases P may be greater than Q, requiring to be moved through a shorter distance.

An example of this is seen in scissors, which are sometimes used to cut stiff material, the cutting being done near the joint, and also to cut light stuff rapidly, when long scissors can be used. Levers which have the fulcrum somewhere between the forces are seen in a crowbar such as is used for lifting heavy weights (Fig. 47), the treadle of a sewing-machine, an air-pump rocking lever, or the beam of a low-pressure engine.

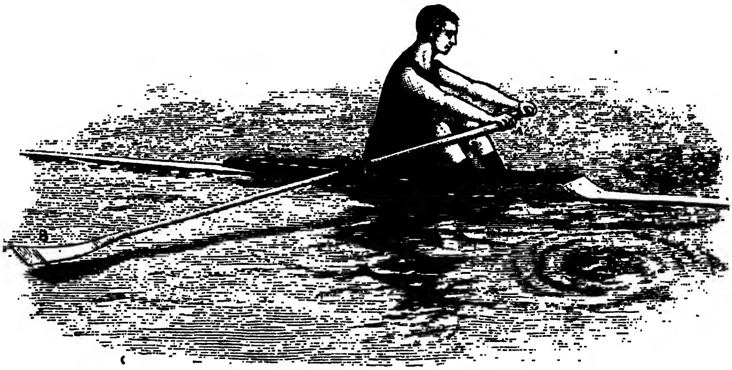


Fig. 48.—Oar as lever.

But it often happens that the fulcrum is at the end of the lever, as in a pair of nut-crackers or an oar (Fig. 48). The sculler is exerting the force at A while work is done at the rowlock C; the blade is supposed to be fixed in the water. In the human forearm (Fig. 49) the force is exerted by the muscle at C, and the lever does the work at A in lifting the weight. In both of these cases forces are applied either at the end or in the middle, the fulcrum being at the end. In the former the sculler applies a less force with his hand than the oar exerts on the rowlock. In the latter case when the weight is lifted the

muscle has to move through a shorter distance than the weight is moved. It is clearly an advantage for the hand to move very rapidly through a considerable distance, while the muscle

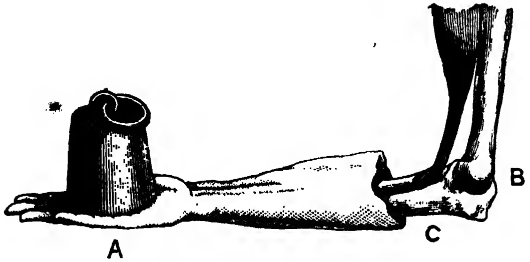


Fig. 49.—Elbow-joint as lever.

contracts with enormous force through a very short space; the mechanical advantage in this instance is less than unity, but the convenience of the agent is attained in the short play of the muscle.

The Wheel and Axle consists of a larger and a smaller wheel fastened together or keyed on the same axle; it is the simplest application of the principle of the lever. A force P is applied at a point A on the circumference of the larger wheel (Fig. 50), and moves it through a small distance r, which need not be shown in the figure. The weight Q is moved through a small distance s at B, on the smaller wheel. The work done by the agent $P \times r$ is equal to the work done by the machine $Q \times s$ (*Principle of Work*) and $P \times AC = Q \times BC$.

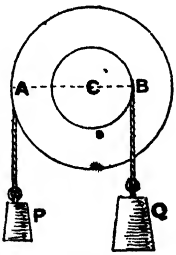


Fig. 50.—Wheel and axle.

The mechanical advantage Q/P depends on the ratio of the radii of the two wheels AC/BC. In the wheel and axle this has a practical limit, for the axle cannot be made too small nor too weak, nor the wheel too large and cumbrous. Some of the water-wheels used in mining operations have a radius of 35 ft., which gives a large advantage to a small flow of water.

A capstan rigged with capstan-bars is 'a wheel and axle,' with

the advantage that forces are applied by the men at different points on the circumference of the wheel. Supposing, for example, that an anchor weighing 10,000 lbs. is to be raised by a capstan whose barrel has a radius of 3 ft., and is rigged with twelve capstan bars. Three men work on each bar at an average radius of 12 ft. (mechanical advantage 4), thirty-six men must each exert a force $\frac{10,000}{36 \times 4}$ lbs., which the mechanical advantage of the machine as a wheel and axle multiplies by 4. Each must put on pressure, *i.e.* apply a force a little less than 70 lbs.

Mechanical advantage may be gained by using a train of toothed wheels (Fig. 51). The wheel C and the pinion B on

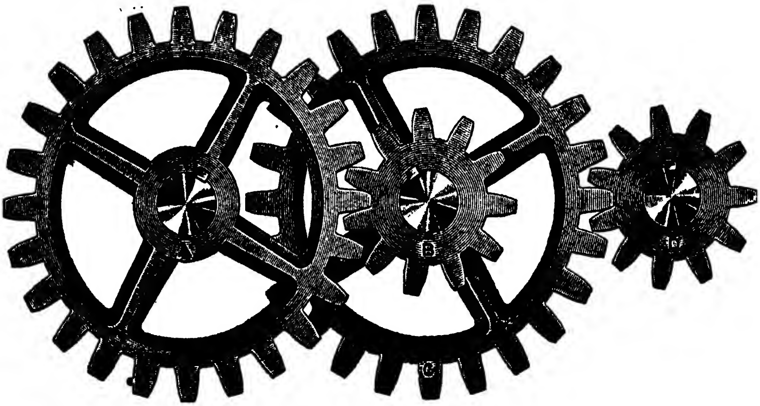


Fig. 51.—Train of wheels.

the same axis is a 'wheel and axle.' The wheels A and C have 24 teeth and the pinions B and D have 11 teeth; the advantage of the system A and B is 11/24 and of C and D also 11/24; the mechanical advantage of the whole system is the product of the mechanical advantage of each pair.

The Differential Wheel and Axle has an endless rope passing round both wheel and axle and also through a pulley attached to the weight. This is much used nowadays in engineering and other shops in the form of a *Differential Pulley*, shown under a ship's stern in Fig. 52. Of the two wheels of the

upper pulley, the nearer is the larger, AC of the outline sketch (Fig. 53).

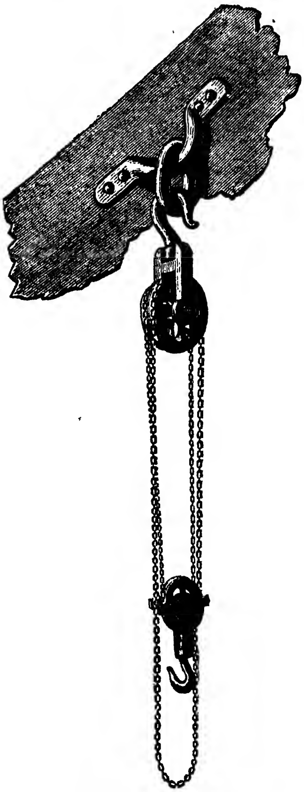


Fig. 52.—Differential pulley.

When a force P does work at C through a small distance r, a length r of the chain is taken on to the upper pulley at D, and a length $AB/AC \times r$ comes off the pulley at B. The rope DWB is shortened by the difference between r and $AB/AC \times r$, *i.e.* by $BC/AC \times r$. The lower pulley is raised by $\frac{1}{2}BC/AC \times r$. The work done on the weight is $W \times \frac{1}{2}BC/AC \times r$, and the work done on the pulley is $P \times r$. As these are equal, the mechanical advantage W/P is $2AC/BC$.

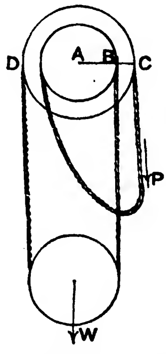


Fig. 53.—Outline sketch.

By making the difference between the pulleys small an enormous advantage is gained, and very heavy weights may be lifted by one man.

The Inclined Plane or wedge is a machine for gaining mechanical advantage by means of two surfaces inclined to one another. The case of a body at rest on a rough inclined plane has been studied above (p. 71).

If an inclined plane be used as a machine it can be studied

by the *Principle of Work;* in this case, the perfect machine being first considered, the plane is smooth.

A heavy ball is moved a small distance up a smooth plane in opposition to gravity by a force along the plane (Fig. 54). Let the force P exerted along the plane move the ball through a small distance r represented by AC, the work done on the body is $P \times r$, at the same time the weight of the ball W has been raised through the vertical height s represented by BC. Then the work done on the machine $P \times r$ is equal to the work done by the machine $W \times s$. The mechanical advantage gained by the inclined plane is W/P, which is given by the fraction AC/BC.

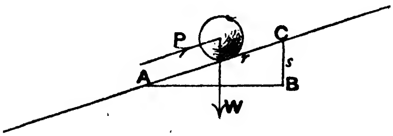


Fig. 54.—Inclined plane.

The Wedge is an inclined plane which is moved by force applied to it so as to do work in enlarging an opening or in lifting a weight.

Let the wedge DG be inserted under a heavy body (Fig. 55), and a force P be applied horizontally at D. Let the force P do work by moving the wedge a small distance r, represented by AB, and lifting the weight W a small distance s, represented by BC. The work done on the wedge $P \times r$ is equal to the work done by the wedge $W \times s$. The mechanical advantage W/P is given by r/s or AB/BC.

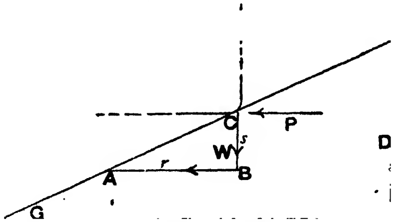


Fig. 55.—Wedge.

The Screw.—If a piece of paper be cut in the shape of a wedge of small angle and be wrapped round a cylinder it will form a spiral curve on the cylinder, which is called 'a screw' (Fig. 56). *The pitch of a screw thread* is the distance in the

direction of the axis between two consecutive turns of the thread.

When the screw is turned round in a corresponding thread, it acts in exactly the same way as a wedge whose angle is that of the wedge-shaped paper with which it was traced. The work done by the force P in raising the weight W through a small space by means of a screw may be examined by considering, as in Fig. 56, the form of the wedge of paper unwrapped from the portion of the screw used. Here the force P has been applied to the screw at its circumference, and moved it through a distance r represented by AB. The portion of the screw thread AC has been used, and has lifted the weight through a vertical distance s represented by BC. The work done on the screw $P \times r$ is equal to the work done on the weight $W \times s$. The mechanical advantage W/P is $r/s = AB/BC$.

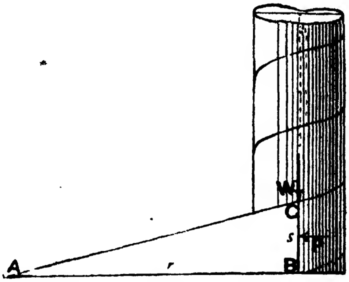


Fig. 56.—Screw, as a wedge.

Supposing AB to be the circumference of the cylinder, AC is one whole turn of the thread, and BC is the *pitch* of the screw, so that the ratio of the circumference of the screw to the pitch gives the mechanical advantage.

An ordinary 1-inch bolt with a Whitworth thread has eight threads to every inch, so that its pitch is $\frac{1}{8}$-inch and circumference is π- or $\frac{22}{7}$-inch. The mechanical advantage is $\pi/\frac{1}{8}$, 8π, *i.e.* about 25.

The force P is applied at the surface of the cylinder and on the screw thread, but it must not be forgotten that a screw is usually operated by a force applied, as in a wheel and axle, by the handle of a screw-driver or spanner, so that an additional mechanical advantage is gained.

A screw A actuates a wheel B whose teeth fit its threads. A combination of the screw and wheel and axle is thus formed

called a *Worm and worm-wheel*, Fig. 57. A great mechanical advantage is gained by this machine, the motion of the wheel being slow compared with that of the worm.

In a musical box the fan has a screw of large pitch on its axis, as A; the wheel B makes the screw rotate rapidly though B moves slowly, and so regulates the slow motion of the barrel. The mechanical advantage is small, but rapid motion is attained.

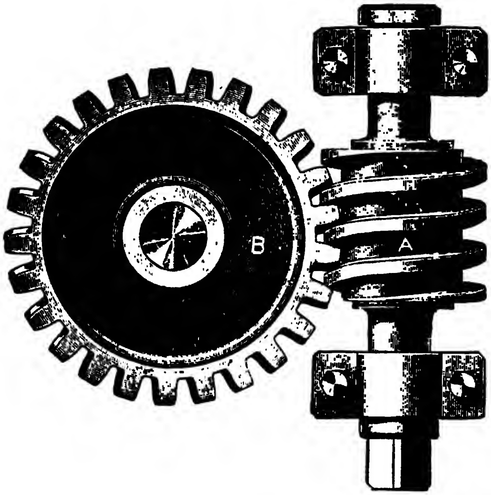


Fig. 57.—Worm and worm-wheel.

In the screw of a steam-vessel the wide blades look like inclined planes, and it is easier to see that the principle is that of the inclined plane. In the earlier steamers a screw with several turns was used, but parts having been accidentally broken off greater speed was found to be attained when the area was small compared with the pitch.

Pulleys.—When a smooth flexible cord passes round a wheel it transmits tension in a changed direction. If work be done on the rope by P in pulling it a short distance *r*, the force W exerted by the rope must do equal work, but as the rope moves a distance *r* through its whole length, the work done

by the rope is $W \times r$. Hence in a perfect fixed pulley, P is equal to W (Fig. 58). This arrangement is called a *a Single Whip;* its mechanical advantage W/P is unity.

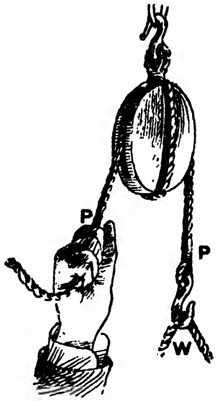


Fig. 58.—Single whip.

If one end of the cord be fixed, and the rope be rove through a block fastened to the weight to be lifted or to some point where work is to be done, the block is called *a Runner* (Fig. 59).

If the weight W be lifted through a small space s, the work done by the pulley is $W \times s$. But for every small space s which the movable pulley rises, the cord moves s at each side, that is $2s$ in all. The work done on the machine is therefore $P \times 2s$, and the work done by the machine $W \times s$. These being equal by *the Principle of Work*, the mechanical advantage W/P is 2.

When two systems of blocks are combined, the product of the purchase, that is the mechanical advantage of each separately, gives the purchase of the whole.

A Runner and Tackle is a combination of two runners. When the lower block (Fig. 60), and with it the weight, is raised through a small distance s, work is done by the machine equal to $W \times s$. Since the cord attached to the upper block and passing round the lower is fastened, the upper block must rise $2s$, as seen before, in the runner. When the upper block rises $2s$, the hand must rise $4s$.

The power P must therefore be exerted on the rope through a distance $4s$. By the Principle of Work $P \times 4s$ is equal to $W \times s$, and the mechanical advantage W/P is 4.

Spanish Burton.—When two cords lead to the weight, one from the hand round a runner, and one from the runner round a single whip (Fig. 61), the mechanical advantage is 3.

If the rope from P round the runner had been fastened as in Fig. 59, the hand would have moved $2s$ when the block moves s,

but as it is attached to the weight, it moves an additional s as the weight rises, making $3s$ in all. By the Principle of Work, the work done by P, $P \times 3s$ is equal to $W \times s$; the mechanical advantage W/P is 3. This arrangement is often used in a yacht to get the ballast out, and is a very handy form of purchase.

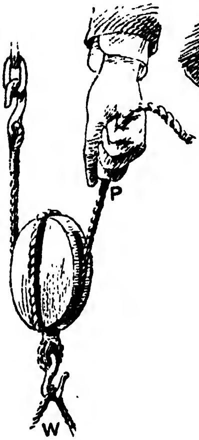


Fig. 59.—Runner.

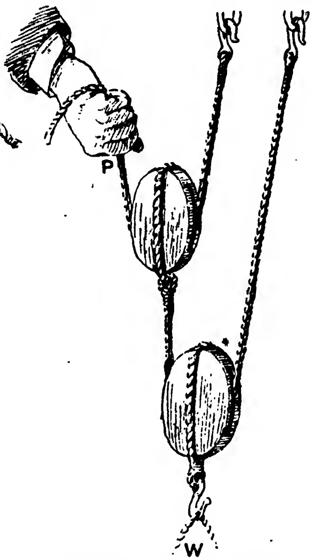


Fig. 60.—Runner and tackle.

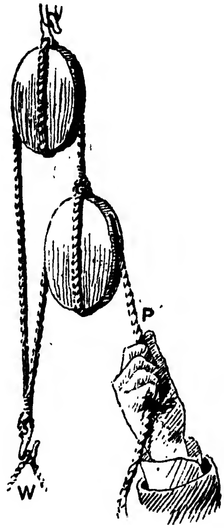


Fig. 61.—Spanish burton.

Purchase.—When a heavy weight is to be raised, blocks with several sheaves are usually employed. When a rope passes round the sheaves of two blocks, one of which is fixed, such an arrangement is called 'a Purchase' (Fig. 62). Suppose that, as in the engraving, six cords go to the lower block. If the weight W be raised through a short distance s, the distance between the blocks is diminished by s. Now as six cords go to the lower block the whole rope, which is between the two blocks, is shortened by $6s$. This must therefore be the length of rope pulled through the upper block by the force P. The work done on the purchase is $P \times 6s$, and this is equal to the work done on the weight $W \times s$ (*Principle of Work*).

The mechanical advantage W/P is 6.

This proves the rule for the advantage gained by purchases :—

The advantage gained by a purchase[1] *always equals the number of parts of the rope in the movable block.*

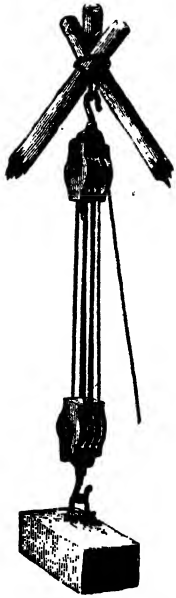


Fig. 62.—Purchase.

In the purchase illustrated, with two 3-sheaved blocks, a weight of 300 lbs. is lifted when a tension of 50 lbs. is applied to the cord, but it is necessary to move the cord through six times the distance that the weight is lifted.

The opposite effect may be produced by reversing the purchase. In a flagship, where it is necessary to send up hoists of flags for signalling purposes as fast as possible, the signal halliards are rove through a purchase such as that illustrated; the movable block is pulled with a force six times as great as that required to send the flags up, the signal goes up six times as fast as the blocks are separated. A man could not possibly send them up so fast by hauling on the halliards, but he can exert six times the moderate force required through a small distance.

Moving Friction.—Hitherto 'perfect' machines have been treated of, which are imaginary in that the surfaces in contact are supposed to be smooth. In practice the friction of the parts must be allowed for, and forms a very important factor in the efficiency of a machine.

That moving friction is less than limiting friction was observed in the experiments for determining the angle of friction (p. 73).

The coefficient of moving friction can be measured similarly. A plane, whose inclination to the horizon can be gradually varied,

[1] This is usually called 'The amount of purchase gained.' Purchase is used in the sense of mechanical advantage in several cases.

is covered with plates of different substances. A weighted box rests on the plane, plates of different substances being fastened to its lower surface (Fig. 63). A heavy hammer is hinged so as to hit and start the box; the height of fall of the hammer, and therefore the initial velocity of the box can be regulated; a spring is so placed as to catch the hammer, and prevent its resting against the box after impact. A pendulum with a bell attachment ticks out equal intervals of time.

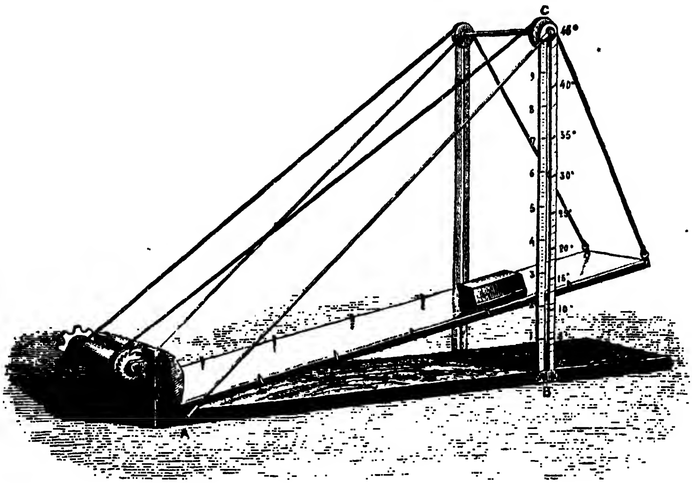


Fig. 63.—Friction apparatus.

The angle of the plane is adjusted so that the box descends the plane with uniform velocity, and this is so when the box passes equally distanced marks at successive ticks of the pendulum. When this is the case the moving friction is equal to the component of the weight along the plane.

The coefficient of friction is the ratio of the friction to the reaction of the plane (BC/AC in Fig. 40), and this is determined by observing the angle of moving friction for each pair of substances.

When one rough surface is moving slowly over another, the laws of moving friction are the same as for limiting friction.

I. The amount of friction varies as the 'load' or pressure.

II. The amount of friction is independent of extent of bearing surface.

"At speeds of less than 100 ft. per minute the friction on journals diminishes with an increase of speed; but at higher speeds with perfect lubrication it increases as the square root of the speed, is independent of the load, but dependent on the extent of bearing surface" (*Molesworth's Pocket-Book*).

Rolling Friction is much less than sliding friction, as may be seen by comparing the slopes on which a round and a flat ruler will rest. However smooth bodies may be, there are small projections and indentations in their surfaces which interlock to a certain extent. When one body rolls over another the motion is not unlike that of a rack and pinion, as the indentations are lifted over one another. It would require considerable force to drag a pinion along a rack without its turning, and the greater the weight of the pinion the greater the force, as it would have to rise over each tooth, —a caricature of Sliding Friction.

To diminish friction in axles, *Friction Wheels* may be used. The axle of the highest wheel (Fig. 64) rolls on the rims of two pairs of wheels, instead of rubbing against the metal surfaces of an ordinary axle-box. Rolling friction is used in *Ball Bearings*, so familiar nowadays, as used in bicycles and illustrated in Fig. 65. This figure is taken from a working drawing supplied by the Hoffmann Company and gives a good idea of the bearings shown in Fig. 26, instead of the familiar friction wheels of Atwood's machine; or the front and side views of a light-running pulley such as that in Fig. 29.

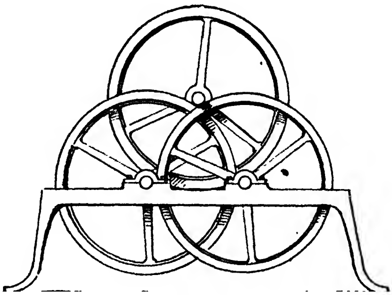


Fig. 64.—Friction wheels.

Roller bearings are coming into use for Railway rolling stock,

with the improvement of materials. Comparative tests were made (March 26, 1906) with two Bengal-Nagpur Railway Company's wagons, the one fitted with fixed gun-metal bearings, and the other with 'Empire' roller bearings. Summarising the results for level rails, the ordinary bearings required a starting effort of $43\frac{1}{2}$ lbs. per ton, the roller bearings only 3 lbs. $6\frac{1}{2}$ oz. per ton.

These bearings have been fitted to the big bell of St. Paul's Cathedral, 'Great Paul,' which with its fittings weighs nearly 25 tons, and the frictional resistance is one-seventh of what it was.

Lubrication is the use of oils or grease between two surfaces which rub against one another. Any lubrication greatly reduces the friction, probably by providing a film which prevents the two surfaces from coming into actual contact.

The variation of friction with temperature, speed, quantity of

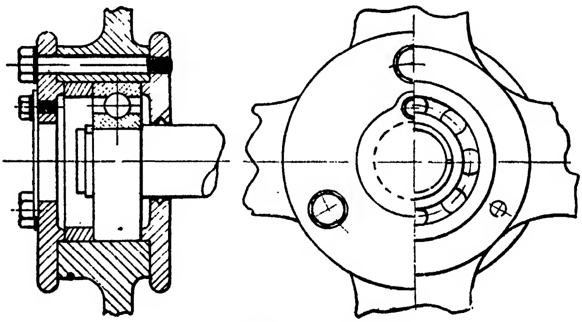


Fig. 65.—Hoffmann Ball Bearings.

lubrication, etc., is not within the scope of this book, but is rather matter for an engineering treatise.

Work done against friction is measured by the product of the friction, and the distance through which the surfaces move over one another. The power of small engines is measured by making them do work against a brake which exerts a constant friction. The product of the speed and the resistance of the brake multiplied by a factor depending on the units employed gives the horse-power of the engine.

CHAPTER VII

Comparative Scales for Computation of Quantities

The Diagonal Scale—Comparative Diagonal Scales—The Metric System—Area and Volume—Mass—Density—Fluid Pressure—Practical Comparisons.

THE difference in the various units of length and mass, and the coexistence of practical or gravitational units of force side by side with the scientific units, make it important to have ready modes of interpreting the value in one unit of quantities expressed in another. The comparison is usually effected by calculation; the number expressing the quantity in one unit is multiplied by a *factor*, the product being the measurement in another unit. The factors for effecting these changes of unit are recapitulated in this chapter.

Besides this, scales are provided by means of which the conversion can be effected without calculation. Comparative or parallel scales are given by which quantities such as—Distance, Area, Volume, Speed, Mass, Force, Density, Pressure, Work, Power, etc., being represented by straight lines, the numerical value of a straight line on one scale represents the measurement of the quantity by one unit, and the numerical value of the same line on the other scale represents the measurement of the quantity by another unit. When it is desirable to make a very exact comparison the factors should be used, but a close approximation can be obtained from the scales by the use of dividers, while for ordinary purposes a distance taken off on the edge of paper gives a sufficiently accurate result.

The Diagonal Scale is so called from the parallel diagonal lines drawn across one of its divisions. It can be used for determining the tenth part of the smallest convenient divisions of any scale: and in general any number of three digits can be taken off a diagonal scale.

In any of the following scales, the outside line being divided into units, the unit above zero is divided into ten parts. Ten vertical lines are drawn parallel to it at equal intervals; the tenth or inner one of these is divided into ten parts. Diagonal lines are then drawn from each division on the unit line to the next division above it on the inner line. It will be seen that each of these diagonal lines at the intersection with each successive parallel rises a tenth of a division. Follow, for example, the diagonal marked 6; at the figure 6 it is 2·6 units —from the unit line marked 2. Where it intersects the first parallel it is 2·61, and at successive parallels it is 2·62; 2·63 . . . 2·69; 2·7 from the line 2.

In this way a scale which has been divided into the smallest convenient divisions, as the unit line is, can be further divided into tenths.

To take a given number off the scale (for example 164).—Place one leg of the dividers on the unit line 1 (N.B., *the first number*), at the fourth parallel (N.B., *the third number*). Open out the dividers till the other leg is on the intersection of the sixth diagonal (N.B., *the second number*) with the fourth parallel. This gives the length of the number 164 on that scale. The important point to be observed is that *the legs of the dividers must both be on the same parallel.*

FACTORS.

Multiply measurements in units on the left by the factor to get measurements in units on the right.

Distance.

66. *Metres, feet* . . .	1 metre	=3·2809 ft.
	1 foot	=0·3048 m.
67. *Inches, centimetres* . .	1 inch	=2·54 cm.
	1 cm.	=0·3937 inch.

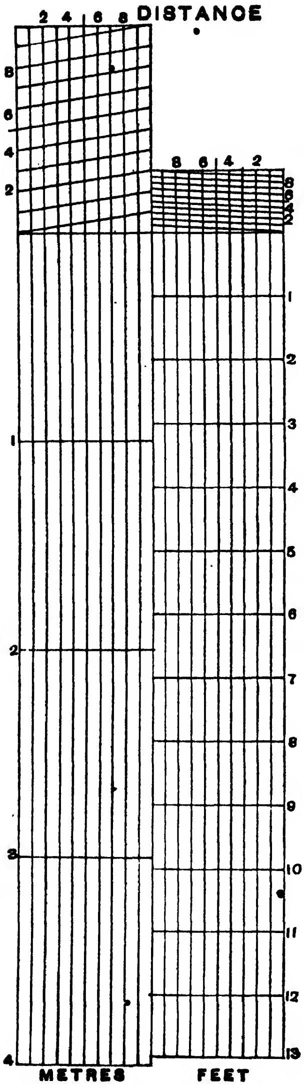


Fig. 66.

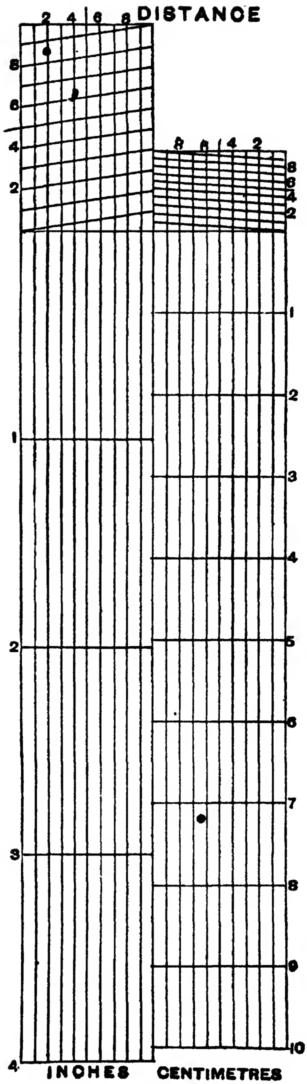


Fig. 67.

To find out what number on the scale corresponds to a given length. The dividers being set to the given length, choose the number of units which is next less than it; keeping one leg on this line and both on the same parallel, draw the point along the unit line until the other leg meets with an intersection of a diagonal with a parallel. The length is represented by the number, of which the first digit is that of the unit line, the second that of the diagonal, the third that of the parallel on which the intersection takes place.

A ——————————————————————— B

For example, the line AB may be taken off on any scale. Choose the scale of MILES. The length of the line lies between 3 and 4. Place the dividers on the 3rd unit line and move them along, the other leg meets the intersection of the 3rd diagonal with the 3rd parallel, the given line represents 333 miles.

This may be 3·33 or 33·3 or 333, according to the value of the unit graduations.

Comparative Diagonal Scales.—To make these scales more accurate they are so arranged that in some cases the number to be taken off must be halved. With this proviso, any quantity may be converted from one scale to another. The number expressing the quantity in one unit is taken off on the scale for that unit, and the number expressing it in the other unit is at once read off on the parallel scale.

For example, a length of 638 miles. Its half, 319 miles, corresponds to 513 kilometres, so that 638 miles corresponds to 1026 kilometres. For another example, a speed of 54·2 miles an hour; in Fig. 69 let the units represent 10 miles an hour. The speed corresponds to 24·3 metres per sec., or 79·6 ft. per sec.

Distance.

68. *Kilometres, miles* .	1 kilometre	=0·6214 mile.
	1 mile	=1·6093 kilom.

Speed.

69. *Metres per sec.* .	1 metre per second	=2·237 miles per hour.
		=3·281 ft. per sec.
Miles an hour .	1 mile an hour	= ·446 metres per sec.
		=1·446 ft. per sec.
Feet per sec. .	1 foot per second	= ·3048 metres per sec.
		= ·682 miles per hour.

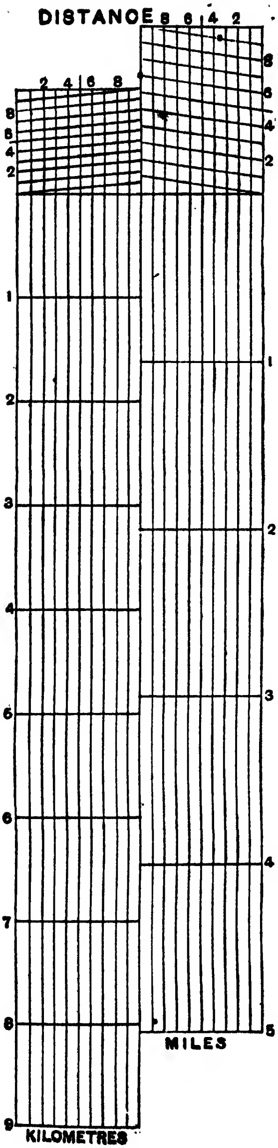

DISTANCE
MILES
KILOMETRES

Fig. 68.

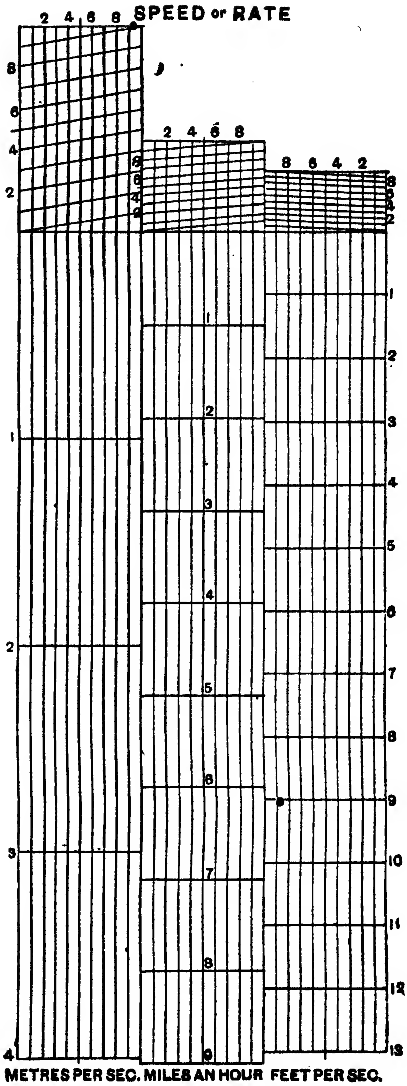

SPEED or RATE
METRES PER SEC.
MILES AN HOUR
FEET PER SEC.

Fig. 69.

The Metric System.—The metrical system is based on the metre; it was originally intended that this unit should be the ten-millionth part of a quadrant of a terrestrial meridian, and a bar of platinum was constructed with great care to be of this length. The length of this bar, which is deposited in the Palais des Archives in Paris, is the STANDARD METRE, and all metrical measurements are consequently made in terms of it quite irrespective of the magnitude of the earth.

It is interesting to notice how nearly the original intention was carried out. The earth is not a spheroid but an ellipsoid; that is to say, the equator is not a circle but an ellipse. The two diameters of the ellipse differ by about two miles and a half. The polar diameter is twenty-seven miles shorter than the mean value of the two diameters of the equator.

The length of the earth's meridian passing through Paris is 10,001,472·5 metres; and the length of the minimum quadrant is 10,000,024·5 metres. The standard metre is consequently about an eighth of an millimetre shorter than it was meant to be. The convenience of the metrical system does not depend on the nature of the unit chosen, the length of the metre is only a conventional quantity given by the length of a certain bar. Its special advantage is that all the multiples and sub-multiples of the unit are given by powers of ten; it is on this account called a 'decimal' system. Multiples of the units are denoted by Greek prefixes, *e.g.* kilometre, hectametre, decametre, which mean a thousand, hundred, and ten metres respectively. Sub-multiples are denoted by Latin prefixes; *e.g.* millimetre, centimetre, decimetre, which are the thousandth, hundredth, and tenth parts of a metre respectively. There are therefore no 'tables' to learn, and reduction is much simplified.

FACTORS.

Area.

70. $\frac{1}{10}$ *sq. metres, sq. feet* .	1 sq. metre	= 10·764 sq. ft.
	1 sq. ft.	= ·0929 sq. metres.
71. *Sq. inches,* 10 *sq. cms.* .	1 sq. inch	= 6·451 sq. cms.
	1 sq. cm.	= 0·155 sq. inch.

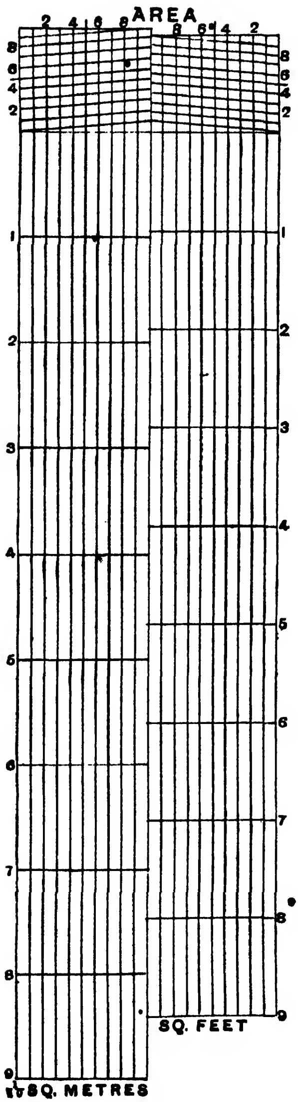


Fig. 70.

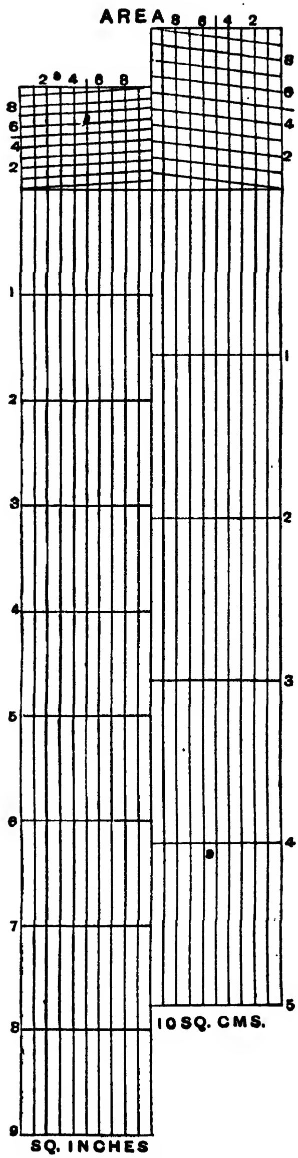


Fig. 71.

Area and Volume.—The square and cubic metre are the standard units of area and volume in the metrical system. For large areas, the *hectare*, which is almost $2\frac{1}{2}$ acres, is usually employed. In scientific investigations, the linear, square, and cubic centimetres are the recognised units.

In cubic measure the *litre* or cubic decimetre is the best known measure; it is less than a quart. Six English 'quart' wine bottles contain a gallon; a litre is about half-way between a reputed quart and a true quart.

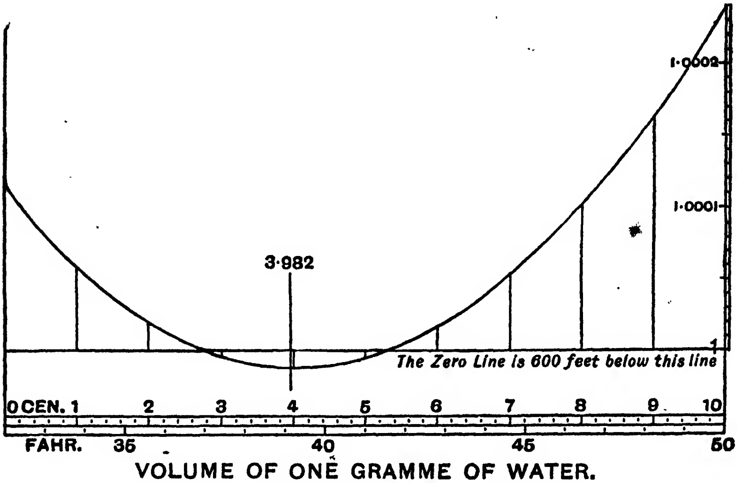


Fig. 72.

Mass.—The units of mass and volume are connected by the mass and volume of water. Water varies in volume with its

FACTORS.

Volume.

73. 10 *cub. cm., cub. inches*	1 cub. cm.	= 0·061 cub. inch.
	1 cub. inch	= 16·383 cub. cm.
10 *Litres, gallons* . .	1 litre	= 0·2201 gall.
	1 gallon	= 4·5459 litres.

Mass.

74. *Kilogrammes, pounds* .	1 kilogramme	= 2·2046 lbs.
	1 lb.	= 0·4536 kilog.

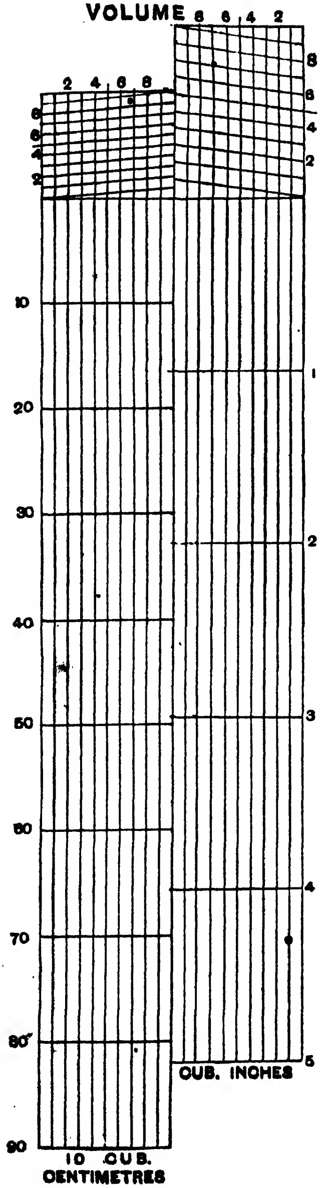

VOLUME
10
20
30
40
50
60
70
80
90
1
2
3
4
5
10 CUB. CENTIMETRES
CUB. INCHES

Fig. 73.

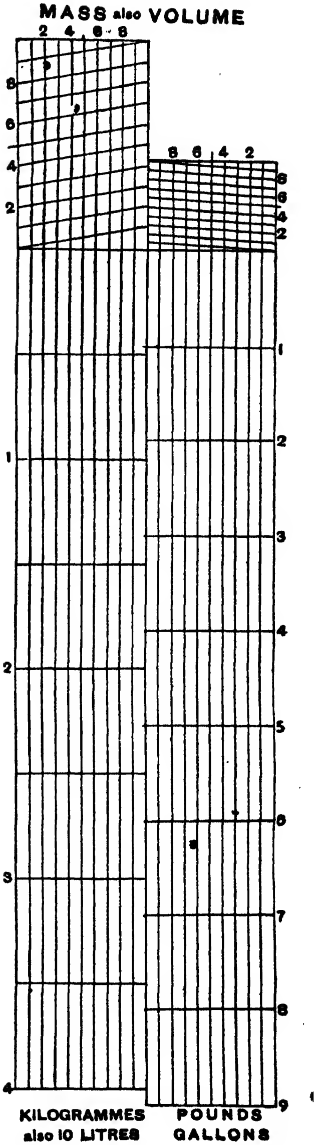

MASS also VOLUME
1
2
3
4
1
2
3
4
5
6
7
8
9
KILOGRAMMES also 10 LITRES
POUNDS GALLONS

Fig. 74.

temperature in a peculiar manner, as is shown in the figure. This figure represents the behaviour of a column of water in a tube 200 yards long, assumed to be of such a material that it does not alter with the temperature. In such a tube a column of water 600 ft. long heated from 0° C. to 10° C. would alternately shrink and expand as shown by the curve. Being smaller at 4° C. (39° F.) than at any other temperature, water at that temperature is taken as the standard substance in many scientific calculations. The unit line in the figure represents a cubic centimetre, and the curve represents the volume of one gramme of water at the different temperatures.

It was originally intended that the mass of one cubic centimetre at 4° C. should be one gramme, and so it is for all practical purposes; it is really so at 2·75° C. and 5·25° C. The gramme was determined by observation and calculation, though, as in the case of the metre, the original intention has not been exactly fulfilled. But, having been thus ascertained, a mass of platinum was made as a standard kilogramme. The mass of this piece of metal, which is deposited with the metre in the Palais des Archives in Paris, is the STANDARD KILOGRAMME, and to it all metrical measurements of mass refer. The litre is the volume of one kilogramme of water.

The BRITISH POUND has no scientific origin or intention; it

FACTORS.

Mass.		
75. 10 *grains, grammes*	1 grain	= 0·0648 gm.
	1 gramme	= 15·432 grains.
Force.		
76. 100 *Poundals*	1 poundal	= 13824 dynes.
		= ·031 lbs.-weight.
Megadynes	1 megadyne	= 72·33 poundals.
	i.e. 10^6 dynes	= 2·247 lbs.-weight.
Pounds-weight	1 lb.-weight	= 32·19 poundals.
		= ·445 megadynes.

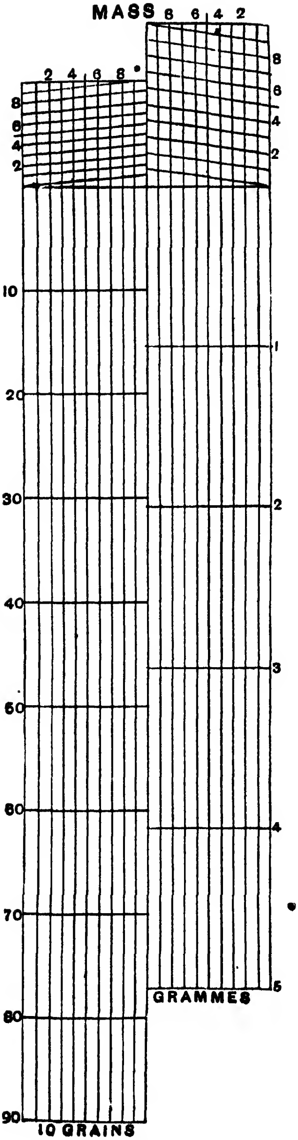

MASS
10 GRAINS
GRAMMES

Fig. 75.

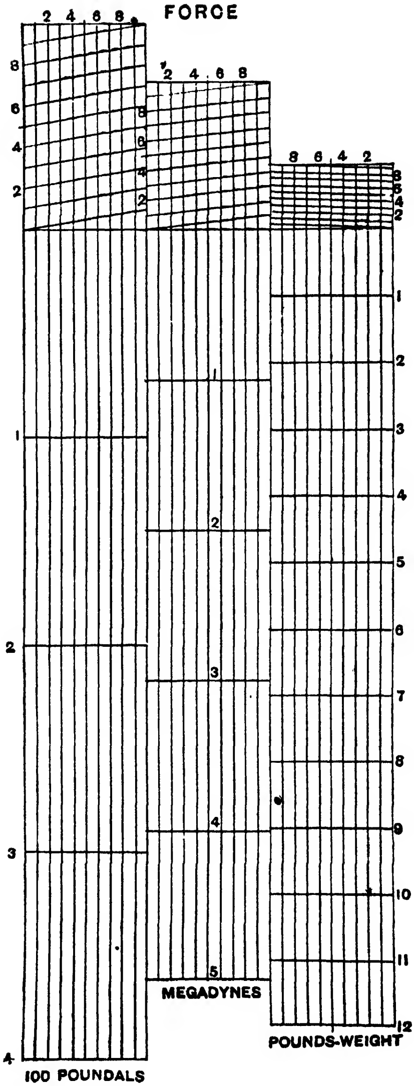

FORCE
100 POUNDALS
MEGADYNES
POUNDS-WEIGHT

Fig. 76.

also is the mass of a certain piece of metal deposited in the Standards Office at Westminster, and to this all English measures refer.

A gallon is the volume of ten pounds of water *weighed in air* at a temperature of 62° F.

A kilogramme is the mass of a litre of water *weighed in vacuo* at 4° C.

For this reason, roughly speaking, a kilogramme must bear the same relation to a pound that ten litres bear to a gallon; also a gramme must bear the same relation to one pound as 10 cub. cm. bears to a gallon.

Being determined by weighing in air, against brass weights and at 62° F., a gallon is *larger* than if the 10 lb. of water had been weighed in vacuo and at 39° F. (4° C.). This difference in the conditions of weighing is shown in the factors, 1 litre = ·2201 gallons; 1 kilogramme = 2·2046 lb., but it cannot be shown in drawing the scales, and therefore one comparative scale does for kilogrammes and lbs. and also for 10 litres and gallons.

FACTORS.

*77. Work Done.

1 Joule = 10^7 ergs =	·102 kilog. m. =	·7374 ft.-pounds.
1 kilog.-metre	= 9·81 Joules	= 7·235 ft.-pounds.
1 Foot-pound	= 1·356 Joules	= ·1385 kilog. m.

N.B.—The erg is the scientific unit of work (see p. 36). The foot-pound and kilog.-metre are practical units:—the work done in raising 1 lb. through 1 ft. and 1 kilog. through 1 metre against gravity.

78. Power.

Horse-power, kilo-Watts . .	1 H.P. = 745·8 Watts.
	1 Watt = ·00134 H.P.

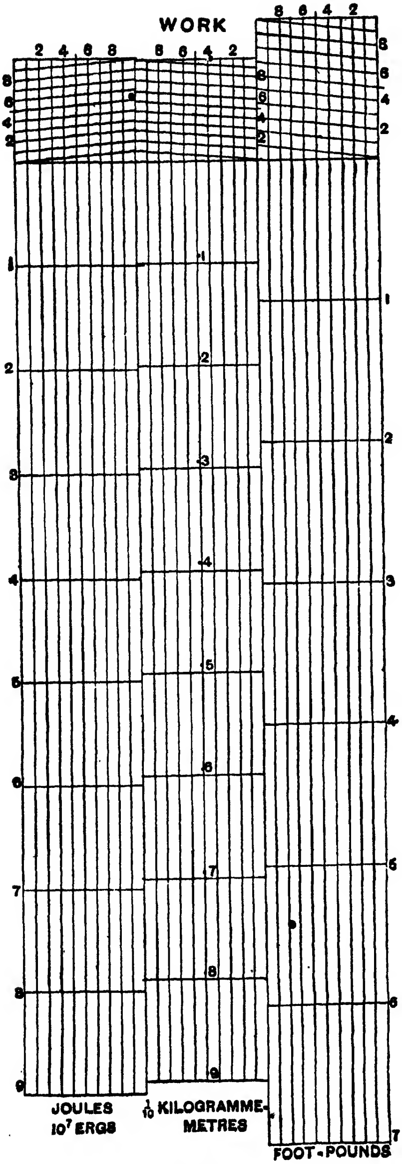

WORK
JOULES
10^7 ERGS
$\frac{1}{10}$ KILOGRAMME-METRES
FOOT-POUNDS

Fig. 77.

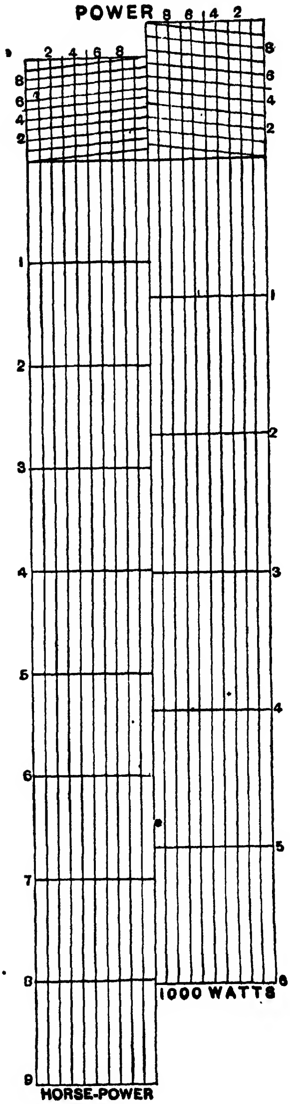

POWER
HORSE-POWER
1000 WATTS

Fig. 78.

It so happens that the mass of a cub. foot of water is nearly 1000 oz. (998·6 oz.); so it is often said that 'a cubic foot of water weighs 1000 ounces.' Now, a litre 'weighs' 1000 grammes. So the relation between a gramme and a litre is the same as between an oz. and a cub. foot, and this is a useful relation in questions of density. It appears in the density diagram (Fig. 79); 80 cub. ft. to the lb., *i.e.* 5 cub. ft. to the oz., being the same density as 5 cub. metres to 1 kilogramme, *i.e.* 5 litres to 1 gramme.

Density.—It is found more convenient to give as a scale for the comparison of densities comparative values of what is sometimes called *specific volume.* In Hygrometry and in the discussion of the steam-engine comparisons of densities appear in this form.

Fluid Pressure.—In the diagram for comparison of measures of pressures, the familiar '*pounds on the square inch*' are compared with the scientific '*dyne on the square centimetre*' and the '*kilogramme on the square centimetre,*' which is the French engineering unit of pressure. The two practical units of pressure are called by their familiar names, and not lbs.-wt. and kilog.-wt. But the student should see the word (*weight*) which is hidden from the practical man, knowing as he does that fluid pressure is a *force* exerted on a certain area.

The normal pressure of the atmosphere is 14·7 lbs. on the sq. inch or 1·033 kilogs. on the sq. cm., corresponding to about 1,013,800 dynes on the sq. cm. This is hardly to be distinguished in the diagram from the megadyne or a million dynes on the sq. cm., which may therefore be called an atmosphere.

FACTORS.

79. Density.

1 cubic ft. to 1 lb.	=62·412 cub. cm. to 1 gramme.
	= ·0624 cub. metres to 1 kilog.
1 cub. metre to 1 kilog.	=16·021 cub. ft. to 1 lb.

80. Fluid Pressure.

1 megadyne on sq. cm.	=14·5 lb. on sq. in.	= 1·019 kilos. on sq. cm.
1 pound on sq. inch	= ·069 meg. on sq. cm.	= ·0709 kilos. on sq. cm.
1 kilog. on sq. cm.	= ·981 meg. on sq. cm.	=14·22 lbs. on sq. cm.

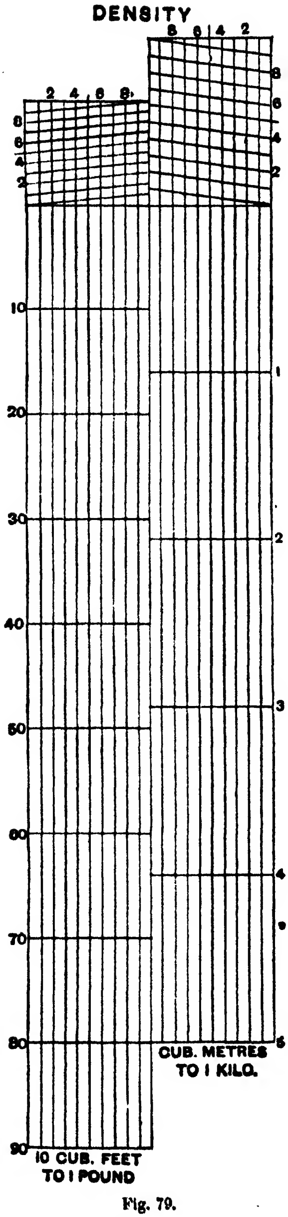

DENSITY
10
20
30
40
50
60
70
80
90
1
2
3
4
5
10 CUB. FEET
TO 1 POUND
CUB. METRES
TO 1 KILO.

Fig. 79.

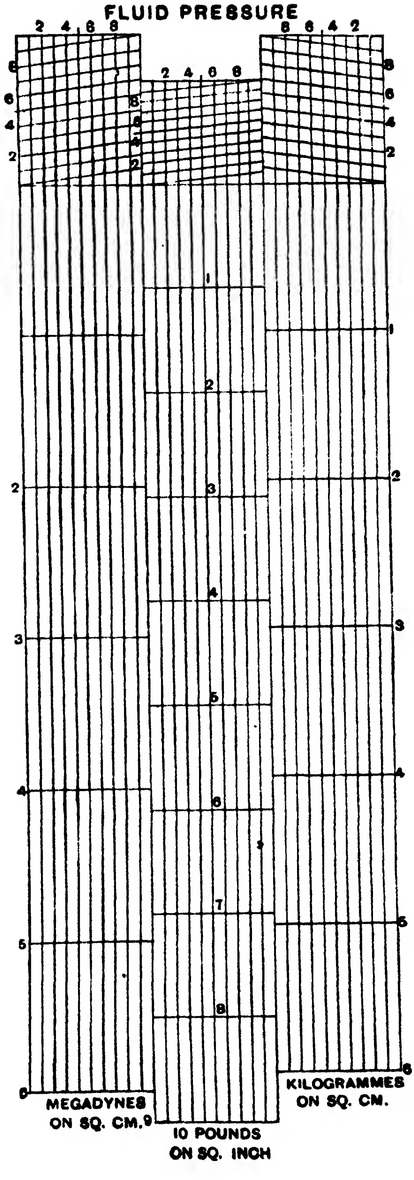

FLUID PRESSURE
1
2
3
4
5
6
7
8
MEGADYNES
ON SQ. CM.
10 POUNDS
ON SQ. INCH
KILOGRAMMES
ON SQ. CM.

Fig. 80.

Practical Comparisons.—A summary of the practical comparisons between the metrical and other systems will be found useful:—

A foot is nearly 30 centimetres.

Eight kilometres make 5 miles.

A square metre is just over 10 square feet.

A hectare is about $2\frac{1}{2}$ acres.

A cubic inch is about 16 cubic cm.

A litre is between a standard and reputed quart.

A kilogramme is about 2 lbs.; while 1000 kilogrammes, called a tonneau, very nearly equals one ton.

The Watt is the rate of doing 1 Joule (10^7 ergs) per second.

The horse-power is the rate of doing 33,000 foot-pounds per minute.

PROPERTIES OF MATTER

CHAPTER I

STRUCTURE OF MATTER

The Three States of Matter—A Solid—A Perfectly Rigid Solid—A Perfectly Elastic Solid—A Liquid—A Gas—A Perfect Fluid—A Perfect Liquid—A Perfect Gas—Properties of Matter—Impenetrability—Divisibility—Molecules—Size of Molecules—Molecular Movement—Crookes' Radiometer—The Structure of Bodies—The State of Gas—Liquefaction—The Liquid State—Solidification—The Solid State.

THIS division of the subject of Natural Philosophy deals with properties of matter, such as Impenetrability and Divisibility, which all matter possesses; with the properties of matter in the three different states—solid, liquid, or gas; and also with properties, such as Porosity, Compressibility, Elasticity, Cohesion, Hardness, etc., which bodies possess to a varying degree. These properties are consequences of the structure of bodies, and in this connection various phenomena, such as Capillarity, Osmose, etc., must be noticed.

Different bodies may possess different properties, even though they be made of the same substance or kind of matter. Iron, as we know it best, is a hard substance, certainly harder than wood; yet an iron-wire mattrass is much softer than a wooden plank. Iron may be drawn out into wire, or rolled into thin plates; by certain treatment it may be reduced to a porous spongy condition; it may be melted or, being intensely heated, may become a gas, in which state it exists in the sun. It is the same material or substance in all these conditions, and yet such iron bodies possess very different properties.

Changes like these, when the form of the body and not the material is changed, come within the province of Physics or Natural Philosophy. There are other changes which are not included in the domain of Physics, as when, for example, iron being exposed to the air, rust is formed on its surface. This is not iron, it is an oxide of iron formed by chemical combination; such a change comes under the heading of Chemistry.

The Three States of Matter.—Matter can exist in three states: viz. as solid, liquid, or gas.

Water is the most familiar example of this, as it exists in the three states, ice, water, and vapour in ordinary circumstances.

ICE is a *solid*, it has a certain shape; it can be handled, and it resists any stress.

WATER has no shape and it cannot be handled, as it offers little resistance to a shearing stress. It has a definite volume and, in a vessel containing more than this volume, it has a 'free surface'; it is the familiar example of *a liquid.*

STEAM or water vapour is *a gas;* it cannot be handled, and has no permanent volume or shape, and it completely fills any vessel.

Though water vapour is generally present in the air, it is not a familiar example of a gas; and experiments in physics on the behaviour of gases are usually made with air.

By these examples it may be seen that Bodies in the three states differ in their behaviour under stresses (see MECHANICS, p. 62), and it is on this that their definitions depend.

A Solid has a definite mass, volume, and shape; it opposes a permanent resistance to any stress.

Two classes of solids, rigid and elastic, are discussed in Mechanics.

A Perfectly Rigid Solid maintains its shape in spite of any stress.

A Perfectly Elastic Solid recovers its form after distortion by any stress, when that stress no longer acts upon it.

A Liquid has a definite mass and volume; it opposes no permanent resistance to any shearing stress; when at rest it takes

the shape of the lowest part of any vessel, with a horizontal 'free surface.'

A Gas has a definite mass; it opposes no permanent resistance to any shearing stress; it completely fills and takes the shape of the containing vessel.

Liquids and gases are classed together as 'fluids'; liquids are sometimes called incompressible fluids, and gases compressible fluids (see pp. 135, 171).

In Hydrostatics, fluids in an imaginary or 'perfect' condition are treated of.

A Perfect Fluid is perfectly mobile, that is, its parts are perfectly free to move relatively to one another, so long as its volume is unchanged; there is no shearing stress in it.

A Perfect Liquid is perfectly mobile and is incompressible.

A Perfect Gas is perfectly mobile and is perfectly elastic in volume, that is to say, if its volume be diminished by stress, the original volume is resumed when the stress is removed.

Properties of Matter.—There are some properties which are possessed by matter of all kinds: Extension or Magnitude, Inertia and Gravity, which have been already discussed; Impenetrability and Divisibility, which will now be considered.

Impenetrability is the name given to the fact that no two portions of matter, however small, can occupy the same space. It does not mean that one body cannot penetrate another, as the word would seem to imply; we know that a bullet can penetrate a block of wood, and that water can penetrate a sponge. In the one case, the portions of the grain of the wood are thrust asunder by the bullet, and in the other the sponge is porous—there are holes in the sponge, which are filled by the water. In neither case are two portions of matter occupying the same space. Impenetrability is a self-evident property, which requires no experiments to prove or to illustrate it.

Divisibility, or the capacity for being divided, is a property of matter which all bodies possess. It is not equally easy to split up all substances, but all bodies can be divided up into very small particles. Instances can be quoted in which very

minute quantities have been obtained by subdivision. Gold can be beaten out till 300,000 leaves are an inch thick. Wollaston was able to make a platinum wire 1/3,000,000 of an inch in diameter, as follows. He encased a platinum wire 1/5 of an inch in diam. with silver; the whole was then drawn out into a very fine wire. The silver having been dissolved in acid, a platinum wire of incredible fineness remained. Again, if powdered chalk be mixed with water, and after some time has been allowed to elapse, for the larger particles to settle, the cloudy liquid be poured off,—when this milky water is evaporated, there remains an extremely fine powder. It is called 'impalpable,' because it cannot be perceived by the touch; yet such a powder is used for polishing, and the fine marks that it leaves on metal show that the particles are possessed of definite shape, though of extraordinary minuteness.

Leslie states (1823) that a grain of musk has been known to perfume a large room for the space of twenty years, and he estimated from this that it contained '320 quadrillions of particles.' There is some doubt as to what a quadrillion may mean, but on one interpretation 'this old computation,' says Tait, 'agrees fairly well with our present knowledge.'

A question naturally arises as to how far this subdivision can go; and the old surmise of Leslie suggests that there is a limit to it, that there are portions of matter which cannot be further divided; on the assumption that this is so, they are called 'molecules' (*lit.* a little mass).

The smallest portion of solid matter that can be obtained —the gold leaf, the platinum wire, the grain of precipitated powder—possesses a shape; its molecules cling together; it is impossible by mechanical means to isolate the individual molecules of solid substances.

But in the case of a gas, the molecules do not cohere, the gas will expand and fill any empty space, however great, so that the molecules become further and further from one another.

In the case of a gas then, we have a substance whose

molecules separate of their own accord from one another. They cannot be seen, it is true, but methods have been devised to give an idea of their magnitude and movements.

Molecules are the smallest portions of matter with which it is the part of Natural Philosophy or Physics to deal. Chemistry seeks further to know how these molecules have been formed of atoms combined in definite proportions. For example, water can exist in three states, as steam, water, or ice; a molecule of water is of the same substance or material, and is always water, whether it be a part of a mass of steam, water, or ice. There is some divergence in the use of the terms 'particle,' 'molecule,' and 'atom' by different writers, but, speaking generally, it may be said: Chemistry deals with the atoms of hydrogen and oxygen, which come under the domain of Physics, as several of them form molecules of oxygen or hydrogen or water, but within the province of Chemistry in the act of combining to form a molecule of water.

Size of Molecules.—There are physical considerations which appear to assign a limit to the magnitude of molecules. Their size has been pictured in various ways: "A cube whose side is the 4000th of a millimetre may be taken as the *minimum visibile* for observers of the present day. Such a cube would contain from 60 to 100 million molecules of oxygen and of nitrogen."—CLERK MAXWELL.

"The best microscopes can be made to magnify from 6000 to 8000 times. A microscope which would magnify the result as much again would show the molecular structure of water."—CLIFFORD.

"If a globe of water the size of a football 16 cm. (6¼ in.) in diameter were magnified to the size of the earth, the molecules or granules would be greater than small shot and less than footballs."—Sir WILLIAM THOMSON, 1883.

"Suppose we magnify a cubic inch (of water) to a cube whose side is the diameter of the earth. In the enormously magnified cube there is one particle to every cubic inch or so." —TAIT.

Molecular Movement.—The molecules of a body are in motion. Bacon and others before him had adopted this explanation of natural phenomena (*Nov. Org.* lib. ii. 20), but it is only of late years that this motion has been brought to the test of experiment and measurement. In a gas, no force is needed to separate the molecules from one another; when a small quantity of gas expands into a large space, the molecules of which it is composed distribute themselves through the whole space. Whatever direct observation has been made of the movement of molecules has been made in the case of an expanded and highly rarefied gas.

It is assumed, and the assumption is borne out by experiment, that the molecules of a gas rush hither and thither, colliding with one another and with the sides of the containing vessel.

Fig. 1.—Crookes' radiometer.

Crookes' Radiometer.—In this instrument, represented in Fig. 1, a light cross with four arms is placed in a pear-shaped glass vessel, so as to revolve easily about a vertical axis. The arms carry square vanes of platinum foil, one side of which is covered with lamp-black.

The air is almost completely exhausted from the pear-shaped bulb, so that the molecules of air are widely separated from one another, and offer little resistance to the motion of the vanes.

When heat-rays fall on the vanes, the lamp-blacked sides become more heated than the foil, and the molecules meeting them are heated. As Bacon surmised, '*the very heat itself is motion and nothing else.*' So, when the molecules are heated at the lamp-black surface, they move faster. Acquiring momentum as they leave the black vane, they must impart an equal momentum to it, and as a consequence of the momentum imparted by many heated molecules, the vanes revolve.

This experiment is one in which the actual momentum of the molecules is, as it were, made evident to the eye.

The theory which this experiment illustrates is called *the Kinetic Theory of Gases.* It assumes that the molecules have a motion of translation, and that the kinetic energy of translation of the molecules depends on the temperature of the gas. The molecules have a potential energy due to their position relative to their mutual attractions; they may also have a kinetic energy of rotation. At present their kinetic energy of translation alone is considered and, for the sake of brevity, is called '*The Energy*' of the molecules.

The sum of the energy of all the molecules in a given mass of gas is called '*The Quantity of Heat*' in that mass.

The mean energy of individual molecules is the same in gases at the same temperature, and may for the present be called '*The Temperature*' of the gas.

When the moving molecules meet with a side of the containing vessel, they lose that part of their momentum which is perpendicular to it. Now change of momentum in unit of time is the measure of force. Hence the momentum thus lost by the molecules which *bombard* a unit of area of the surface in a unit of time is the measure of the force which the gas exerts on unit area of the containing surface. This is called '*the Pressure*' of the gas.

The pressure may be reduced either by diminishing (the number of molecules in unit volume, that is) the density of the gas or by reducing (their energy, that is) the temperature of the gas.

An attempt was made above to give some idea of the size of molecules, their magnitude is assumed to be about the same for all bodies, their mass and velocity to vary considerably.

The average velocity of the molecules of hydrogen at a temperature of 0° C. has been ascertained to be more than a mile (1859 metres) per second. In oxygen, at the same temperature, the velocity of the molecules is one-fourth of this, their mass being sixteen times that of hydrogen molecules, and the mean energy being the same.

In the atmosphere the number of collisions per second between particles is practically infinite, and a molecule travels on an average 1000 times its own diameter without colliding with another. But if the air be rarefied, the collisions are less frequent, and the 'free-path' of a molecule is greater. In an ordinary Edison-Swan incandescent lamp the air is so highly rarefied that the space is practically void of air, the pressure being estimated at one hundred millionth of the ordinary pressure of the atmosphere. In these conditions, the number of molecules in unit volume is reduced to one hundred millionth, and the distances which they travel without collision increased to the same extent, so that their numbers and distances come within the powers of human observation. The free path of a molecule of air in such a 'vacuum' is about 35 feet.

The Structure of Bodies—The State of Gas.—In speaking of Divisibility, it was observed that the smallest portion of solid matter which can be obtained consists of several molecules, and has a definite shape, but that in a highly rarefied gas the molecules are widely separate. The size of these molecules and their movement has been discussed; a gas has been described as being composed of molecules in rapid and independent motion. Such a body (for though it be small this rarefied gas will have a certain mass, and may be called a body) has a very simple structure; it has no cohesion, it has only molecular energy.

An endeavour may be made to portray the structure of bodies in the three states by tracing the changes of a mass of such a body of expanded and highly rarefied gas, as it is successively compressed and cooled until the solid state is reached.

Water affords the most familiar example of the three states of matter. The body to be considered will therefore be—

A GRAMME OF WATER AT A TEMPERATURE 4° C. (39° F.).

At this temperature a gramme of water exists as a gas so long as the pressure on it is less than 6·10 mm. (·238 in.) of mercury, and so long as more than 160,120 cub. centimetres are allowed

for its volume (see pp. 323 and 339). It can be expanded to any degree of tenuity by increasing the volume it is allowed to occupy, and it is in this rarefied condition that its structure was examined above. As has been observed, the highest degree of divisibility has been attained. Its structure is extremely simple; it has no cohesion, it has only movement and energy of its molecules.

Molecular attraction is very powerful when molecules are not separated by sensible distances; but in a gas at ordinary pressure there is practically no molecular attraction.

Liquefaction.—Let the volume be decreased, the temperature remaining the same; the number of molecules in unit volume is increased, while the energy of individual molecules is unaltered. At the pressure and volume stated above, a condition is reached when the number of molecules per unit volume is so great that their movement is only just sufficient to keep them clear of the attraction of other molecules. When the volume is further decreased some molecules are brought within reach of the molecular attraction of others. If some body wandering through space were forced to approach so near to the sun that its velocity was that of a similar body performing an orbit, henceforth the body would circle in an orbit round the sun. It would lose its 'free path'; its momentum would be destroyed.

The Liquid State.—So the molecules of gas having been brought nearer to one another by compression, become involved with one another in the perfect equilibrium of bodies performing orbits. A mass of molecules so engaged is in the liquid state of matter; they have lost the momentum which made them rise in spite of gravity, just as two dogs fighting with one another may roll over a precipice. They lie at the bottom of the vessel or find some solid surface to cling to in the form of drops.

The volume being still further reduced, no increase of pressure is observed; the molecules which still preserve their free path and motion have the same energy and exert the same

pressure. But as compression proceeds, more molecules are entangled, and when the volume of one cubic centimetre is reached the whole mass becomes liquid.

Then further compression is met by a very great resistance. In the liquid condition the motion of the molecules in orbits round one another must be extremely rapid, and the great resistance of liquids to compression, which has earned them the name of incompressible fluids, may be considered as due to compressive disturbance of these orbits.

During the change which we have pictured from the free and gaseous condition to the liquid state, the temperature has not been altered. The change of state has been brought about by reduction of volume. Liquefaction might have been produced by diminishing the energy of the molecules, *i.e.* the temperature, the volume remaining the same. There is a maximum pressure of water vapour for each temperature (see pp. 323 and 325). That is the condition when the number of molecules per unit volume is so great that their motion is only just sufficient to keep them clear of the attraction of other molecules. When the energy of the molecules is diminished, some of them are brought within reach of the molecular attraction of others and liquefaction commences, their energy being less, the pressure of the vapour is less.

So long as there is free space above the liquid, it will be occupied by vapour at the maximum vapour pressure, and the only way of liquefying the whole mass of vapour is by diminishing its volume to one cubic centimetre.

Solidification.—The whole mass being now liquid, the energy of movement can be reduced by diminishing the quantity of heat in the mass. As the temperature is reduced, a point will be reached when the molecule has not sufficient energy to continue in its orbit. What we may call, in common language, 'the centrifugal force,' is not sufficient to oppose the molecular attraction; the molecules adhere to one another, and vibrate as the extremities of a tuning-fork vibrate. This is beautifully seen in the crystals of ice which form when water is

gradually cooled. The molecules cling together and gradually build up slender crystals.

The Solid State.—The directions of vibration of the molecules of different substances no doubt determine the form and structure of the mass, if it is free to solidify in any shape.

The grain of solid substances is intimately connected with their strength to resist stresses in different directions. As this strength is due to molecular attractions, the directions of these vibrations must affect it.

When a body, heated iron for example, is near its melting point it is weak; the motion of the molecules neutralises their attraction.

The temperature of the mass being the mean energy of individual molecules, as this is diminished the vibration is lessened. Could all the heat be removed, there would be no vibration, no energy of movement, and the body would have reached that absolute zero of temperature which Fahrenheit thought he had reached in his zero, if Newton did not in his;—that unattainable zero which is to the physicist what the North Pole is to the explorer.

Some apology is perhaps necessary for the introduction of such a highly ideal picture of the molecular constitution of bodies; it may present too great difficulties to the beginner; but, on the other hand, the ideas are suggestive, and as the various subjects are more particularly studied afterwards, it will be referred to. It is possible that in the end the various ideas may be helpful to the mind, as a picture, however rough, may be used to help a learner.

CHAPTER II

Effect of Molecular Forces

Molecular Forces—Surface Tension—Capillarity—Viscosity—Porosity—Compressibility—Cohesion—Hardness—Tenacity—Rigidity—Elasticity—Fatigue of Elasticity—Plasticity—Malleability—Ductility—Diffusion—Colloids and Crystalloids—Osmose.

Molecular Forces.—The magnitude of the mutual attraction of molecules has been shortly referred to in the former chapter as powerful only when the molecules are not separated by sensible distances.

Experiments have been made with the object of ascertaining at what distance the molecular forces are felt. Their influence has been detected through a film of silver ·000005 cm. (two millionths of an inch) thick, *i.e.* one-tenth of the length of a wave of green light.

In solid bodies the magnitude of these forces must be enormous. The tensile strength of mild steel is as much as 30 tons per square inch, and this is the measure of the molecular attractions in that substance.

In liquids the molecular forces are comparatively small, but they are not negligible. If the clean surface of a glass plate be brought into contact with a clean water-surface, such an arrangement as is shown in Fig. 2 being used to measure the force of adhesion, 60 grains-weight per square inch is necessary to separate the surfaces. Glass and mercury, if carefully cleaned, have an adhesion of 180 grains-weight per square inch; amalgamated zinc and mercury, 500 grains-weight per square inch.

This last value is apparently the measure of the molecular attraction in mercury, as the amalgamated zinc has a surface of pure mercury.

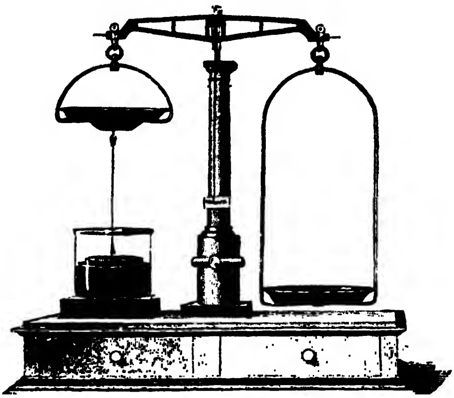


Fig. 2.—Measurement of adhesion.

In a gas at ordinary pressure there is practically no molecular attraction.

Surface Tension is the magnitude of the force which can be applied to a section of surface of a liquid without its separating.

When liquid is 'brimming over' it has a curved edge; when it falls it has a curved surface (Fig. 3). If a needle be greased and gently placed on a surface of water it will lie on the surface and form an indentation; in the same way insects can walk on the surface of water.

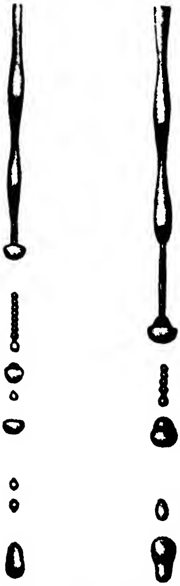


Fig. 3.—Falling water.

If the surface of any liquid be examined, it has all the appearance of being covered with an elastic skin. It requires some force to break this skin, and the force varies with different liquids. This phenomenon is due to the molecular attractions. A molecule within a mass of liquid is in equilibrium, as the molecules on all sides of it are attracting it equally. But a molecule on the 'free surface' of a liquid is not attracted by molecules on the side away from the liquid. We might picture a small hemisphere of liquid, all the molecules of which attract the surface molecule, which is its centre; by the resultant of these unbalanced forces, every molecule on the surface is drawn towards

the mass of the liquid, and the surface of the liquid takes that shape which has the least area possible under the conditions. This is the reason that a small quantity of water, such as a rain-drop, takes a spherical shape.

The spherical form of a liquid in equilibrium is shown thus:—

Alcohol being lighter and water heavier than oil, a mixture of alcohol and water can be made of the same weight, volume for volume, as oil. If some oil be placed in a mixture of this kind by means of a pipette, it remains suspended in equilibrium, and assumes a spherical shape.

Shot towers are used for making shot by letting molten lead fall through a sieve from a considerable height. The shot cool in a spherical form as they fall, being received in a cistern of water.

The magnitude of the surface-tension depends on the nature of the liquid and of the substance in contact with it.

The following values of surface tensions are given by Quincke in C.G.S. units at 20° C.:—

Liquids in contact with	Air,	Water,	Mercury.
Alcohol . .	25·5	...	399
Water . . .	81	...	418
Mercury . .	540	418	...

The unit employed being one dyne per linear cm., divide by 25 to reduce to grains-weight per inch.

The behaviour of liquids in contact with solid substances depends on whether the liquid 'wets' the solid or not. If it does, it clings to it with a force which has been measured by the apparatus (Fig. 2), and can be shown by experiments.

If two or three drops of distilled water fall on a very clean surface of glass, the water spreads over the glass in the thinnest possible layer. As the water 'wets' and adheres to the glass the surface-tension extends it as far as possible. Now, place a very small drop of spirit on the surface of the water; then the surface-tension of alcohol being so much smaller than that of water, the stronger tension of the water will pull away the spirit, and leave the glass bare.

The surface-tension of liquids decreases with a rise of temperature, the same effect will therefore be seen if a hot poker be approached to the water; the tension is weakened, and the glass dries, under the poker.

If a little oil be placed on the surface of water, the tension of its surface is so weak, compared with that of water, that the oil is spread into the thinnest possible film.

This explains the difficulty which there is in keeping clean a surface of clean water or of pure mercury. The surface-tensions of water and mercury are so much greater than those of other liquids whose vapours may condense on them that if the clean surface is left exposed, it is soon covered with a film.

If benzine is used to remove a spot of grease from cloth, the grease should be surrounded with a ring of benzine; the grease, having a greater surface-tension, collects towards the middle, whence it can be removed with blotting-paper. If the benzine be put on the grease spot, the grease is spread over the cloth and cannot be removed.

Some of the most beautiful demonstrations of surface-tension have been made in experiments with soap bubbles. The shapes assumed are all those of the figures which have the least area under the conditions (Boys, *Soap Bubbles.* S.P.C.K., 1890).

Capillarity. — If a fine glass tube, whose bore has been thoroughly cleansed, be dipped into clean water, the water will wet the inside of the tube and rise in it. The fact that water will rise to a considerable height in fine hair-like tubes is called Capillarity (*lat.* capilli, *hairs*). The height to which liquid rises in a tube depends on the nature of the liquid and on the diameter of the tube.

This rise of liquid in fine tubes is due to the molecular forces which cause surface-tension. At any point, just underneath the free surface, the pressure must be less than that of the atmosphere by the amount of the unbalanced molecular attraction of the surface film. A column of water rises in the tube, whose weight is equal to the total upward molecular attraction of the surface film on the molecules next to the surface.

The height of the liquid varies inversely as the diameter of the tube. In Fig. 4 five tubes of differing bore, the largest being on the left, are seen dipping into a dark liquid which rises in the bore, the rise being highest in the small tube on the right.

In the same figure, and behind the tubes, are seen two glass plates, near to one another, but nearest on the right hand. In this case the liquid rises higher when the plates are nearer together, taking the shape shown in the figure.

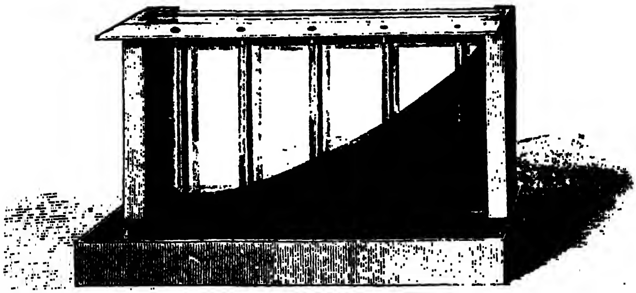


Fig. 4.—Capillarity: plate and tubes.

The atmometer, illustrated in Fig. 5, may be used to show how large are the forces exerted in capillarity.

This instrument is designed to measure the amount of evaporation from a wetted surface (HEAT, p. 320); a bulb of 'biscuit' clay, into which is luted a long glass tube, is filled with water and inverted into water. If instead the tube stands in a vessel of mercury; as the water evaporates the mercury will rise to take its place. The capillarity of the fine pores or tension of the small water surfaces at the end of them draws up the mercury until, as evaporation proceeds, the column stands at a height of 760 mm. (29·92 in.) above the surface of the basin. The experiment shows that the molecular forces exert a tension greater than the atmospheric pressure, but it cannot be measured, as this method cannot measure a tension greater than this.

So far, the surface of liquids which 'wet' solid substances and adhere to them has been described. Liquids which do not 'wet' a solid surface behave differently. In this case the

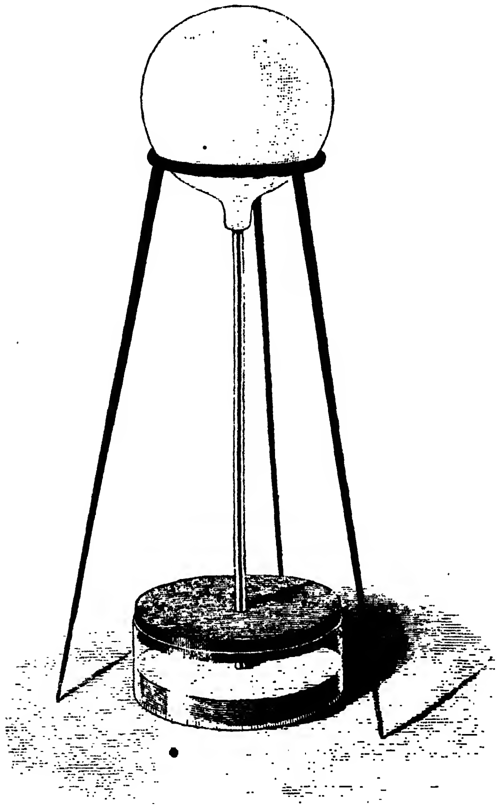


Fig. 5. Atmometer.

liquid appears to have a skin which leans against the 'unwetted' surface.

Fig. 6 shows in section the shape of the surfaces of mercury and water in a glass tube, or perhaps better of water in a clean tube, and also in one which has been lined with a film of vaseline.

The surface of water in the 'greasy' tube B is depressed below the surface of the water outside the tube, while the water in the 'wetted' tube A stands above the water outside.

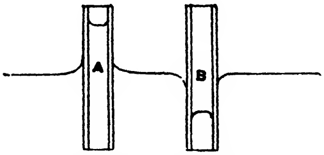


Fig. 6.—Capillarity: wetted and unwetted tubes.

Correction must be made for capillarity in reading a barometer accurately, as the reading will be lower than it should be, markedly so with a tube of small bore.

There are many phenomena to which 'capillary attraction' is ascribed as a cause. The rise of oil in the wick of a lamp is due to the surface-tension at the extremity of the fine pores existing between the twisted threads. The spread of water through a lump of sugar, the rise of sap in plants and trees, are due to capillarity.

A familiar experiment for showing the behaviour of wetted and unwetted surfaces is shown in section in Fig. 7. A

Fig. 7.—Capillarity: pairs of floating spheres.

number of painted cork balls are weighted so as to float half immersed in a basin of water. The surfaces of some of them, A, B, E, H, are cleansed from any grease; these are wetted by the water, while others, C, D, F, G, are covered with a film of vaseline, and are not 'wetted.'

Those pairs which are both wetted or unwetted attract one another, but a wetted ball and an unwetted ball repel each other.

Viscosity is the resistance offered by fluids to shearing stress. A perfect fluid offers no resistance, it is perfectly mobile; it is not viscous. Viscosity varies with the nature of the fluid; gases are very mobile, yet the viscosity of air is seen in the effect of wind in raising waves; if air were not viscous, its passage over smooth water would have no such effect. The pressure of wind on sails and the resistance of the air to a bullet or falling bodies

exert forces, not wholly due to viscosity, but to the change of momentum of the air displaced. An illustration of the viscosity of air has been given in MECHANICS, Fig. 21, p. 45, the 'Guinea and feather experiment.' By the behaviour of a coin and a feather in a tube from which the air has been exhausted, the slow motion of a light body when falling is shown to be due to the resistance of the air.

WATER HAMMER.—This is a tube (or tubes, as shown in Fig. 8) which is half full of water, all the air having been removed by boiling before the tube was sealed with a blow-pipe. The water falls from end to end with a blow like a hammer, showing at once how little compressible water is, and how in ordinary circumstances the air cushions a fall. In both these experiments the viscosity of the air is made evident by the unfamiliar effects which appear when air is absent.

Fig. 8.—Water hammer.

The viscosity of gases has not been determined by experiments, but by calculation from dynamical considerations, particularly by the late Professor Clerk Maxwell. He says that viscosity of gas is not dependent on density, and that it increases with the temperature; also that hydrogen has half the viscosity of air, and that oxygen, air, and carbonic acid are viscous in descending order of magnitude. A piece of common experience illustrates this. When a gas pipe has been repaired, it is full of air, and when the tap is turned on the air rushes out first. The ear detects that the air has all come out by the softer sound made by the carburetted hydrogen, which shows that it offers less resistance.

The coefficient of viscosity in a fluid is the tangential stress on 1 sq. cm. of each of two parallel surfaces 1 cm. apart, moving at the rate of 1 cm. per sec.

The viscosity of liquids is greater than that of gases. The

following is a simple mode of comparing the viscosity of liquids. Fill a funnel up to a given mark with different liquids and observe the time taken by each liquid to run out. Spirits and mineral oils are very mobile; water, mercury, vegetable and fish oils are not very viscous; glycerine, treacle, tar and pitch much more so. The time element in viscosity must be noticed; if a stick of sealing-wax be unsupported except at its ends, it sags and falls in time; a thin piece of wood, which breaks much more easily, would not perceptibly sag more after the lapse of a day; it is a solid, while the sealing-wax is a very viscous liquid. Pitch flows more quickly than most people imagine; a cask of pitch left one night on the laboratory floor (without the cork) had by the morning spread over the floor and swallowed up the loose articles left about. A stream of pitch flowing out of the open bung-hole of a cask left standing on its end in a dockyard had the appearance of a stream of ink instantaneously frozen. Pitch has, however, a certain number of the characteristics of a solid, and has to be treated as an exception to most general laws.

If small basins be filled with any of the liquids mentioned above (except pitch), a smart blow on the side with a wooden mallet causes ripples on the surface. The size and duration of these ripples afford a measure of viscosity.

The viscosity of liquid diminishes rapidly with a rise of temperature. Poiseuille has calculated the coefficient of viscosity of water in C.G.S. units at 0°, ·018; at 10°, ·013; at 20°, ·010.

Porosity of bodies is the fact that in every body there are pores and spaces in the substance which are not visible to the naked eye. Some bodies, such as coke, sponge, and cork, have large visible holes in them. This is not what is meant by the term 'porosity' in Physics. Substances, such as gold, silver, iron, lead, etc., which appear close-grained are nevertheless porous in the sense that their molecular structure is not continuous, and there are interstices which can be occupied by other matter.

Experiments were made at an early date to find out

whether water is incompressible; they failed because of the porosity of the containing vessel. Bacon squeezed and hammered a leaden shell full of water, but the water came through the lead. The Florentine Academicians tried the same experiment with a globe of silver; and, finding that the water oozed through, they had it thickly gilded, only to find gold porous also.

Hot iron is very porous to carbonic acid; a fact which should be remembered, as this gas is poisonous, and, being given off in large volumes from burning coal and coke, is a source of danger in an unventilated room with a stove. Platinum when heated is pervious to hydrogen.

The interpenetration of two liquids, such as alcohol and water, or sugar-syrup and water, is often chosen as an example of the porosity of liquids. If a tumbler be 'brim full' of warm water, a large amount of sugar may be dissolved in it with care without its overflowing.

A mixture of 27 parts of water and 23 parts of alcohol occupies 48·8 parts instead of 50; but the temperature of the mixture is 8° C. above that of the original liquids. A rise of temperature is a sign of chemical action, and cases of absorption of fluids by liquids and solids must be quoted with caution as instances of porosity.

What has been said of the structure of gases might lead to the conclusion that they were the most porous of bodies. Porosity is the fact that two bodies may occupy a space which is less than the sum of their dimensions owing to one penetrating the pores of the other. The dimensions of a gas are its pressure and volume.

Gases, then, are not 'porous'; if equal volumes of gas at different pressures be mixed in a vessel of equal volume, the pressure of the mixture is the sum of the separate pressures.

Porosity is used in various ways; especially for purifying liquids by straining them through the pores of substances. Blotting-paper filters are largely used by chemists. In the silicated carbon filter (Fig. 9) the water is strained through the

pores of the block which the arrows are seen to traverse. The block can be removed and cleaned.

Compressibility is the property of bodies in virtue of which they may be induced by pressure to occupy a smaller volume. Compression would be impossible but for porosity. If a body, all of whose volume is occupied by matter, were compressed, matter would be obliged to enter space already occupied by matter.

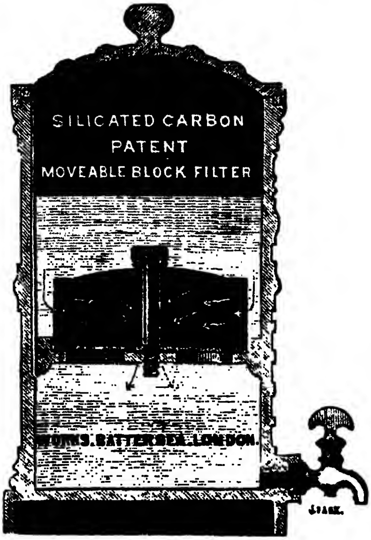


Fig. 9.—Silicated carbon filter.

The structure of bodies which has been described, viz. their composition of molecules in motion, agrees with the observed facts of compression.

Gases are called *compressible fluids*, because the permanent gases, oxygen, nitrogen, hydrogen, etc., yield so easily to pressure. If a plunger fit air-tight into a closed glass cylinder (Fig. 10), it can be forced into the tube so as to compress the air to any extent, and it rebounds when released. This experiment shows that air is compressible. The volume of a gas depends on the pressure and temperature of the gas.

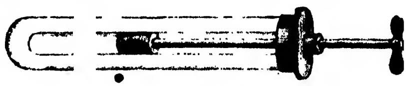


Fig. 10.—Pneumatic syringe.

A gramme of air occupies 769 cub. cm. and a gramme of hydrogen 1160 cub. cm. at a temperature of 0° C. and the ordinary pressure of the atmosphere; but at any other pressure the volumes occupied are different, if the temperature remain the same. The law of Compressibility of Gases was published by Boyle in 1660, and by Marriotte, without referring to Boyle's discovery, in 1679. The subject is further discussed in HYDROSTATICS, Chap. III., and HEAT, Chap. II.

Liquids are called *incompressible fluids,* in contradistinction to gases, because gases yield so easily to pressure, while it is only under great pressures that there is any perceptible compression of liquids. For a long time water was believed to be incompressible; the experiments of Bacon and of the Florentine Academicians referred to above, as showing the porosity of lead, silver, and gold, were held to prove that water is incompressible.

OERSTEDT'S PIEZOMETER shows the compression of water or of any liquid very plainly. The water or liquid to be experimented on is contained in the tube A (Fig. 11), which is drawn out into a fine curved tube with a bend at B, in which is some mercury. The whole is placed in a vessel with thick glass sides filled with water by the funnel F. Pressure is brought to bear on this water by the screw S acting on a plunger in the strong cylinder P. As there is the same pressure on the outside and inside of the tube A there is no danger of breaking it, and the liquid in it is compressed, as is shown by the movement of the mercury at B. The amount of the pressure is measured by the compression of the air sealed into the tube XY by a thread of mercury. The mercury reaches the mark half-way between X and Y, when an additional pressure of one atmosphere is put on by the screw. As the glass of the tube A is also compressible, allowance must be made for this. It is found that water is compressible to the

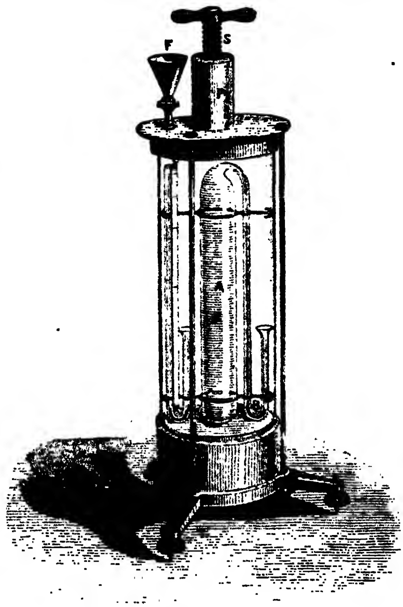


Fig. 11.—Oerstedt's piezometer.

extent of ·00005 of its volume for every atmosphere of pressure. Amagat has used pressures reaching 4000 atmospheres, concluding that water at 0° C. cannot be reduced to less than ·7 of its volume.

Specimens of deep-sea life are obtained by securing water from a depth of 3000 fathoms; provision must be made for a considerable expansion of the water when it reaches the surface.

Solids are in general less compressible than liquids; but mercury is less compressible than glass and must be classed with solids. India-rubber is a very compressible solid. The compressibility of a solid has much to do with its elasticity, and for this reason the subject is better discussed later under the head of Elasticity.

The Coefficient of Compressibility is the quotient of the pressure by the compression, *i.e.* by the ratio of the change of volume to the original volume.

Compressibility is not the same as the strength of a material to resist a compressive stress. This is called in engineering books the 'crushing strain'[1] or 'crushing weight,' and depends on cohesion.

Cohesion (*lit.* clinging together) is the power of the molecular attractions to hold together parts of the same body or different bodies in close contact. A distinction is sometimes made between cohesion and adhesion, the former being restricted to the molecular attractions inside a body and the latter to the attraction between two different bodies. Molecular forces act sensibly when the molecules are not separated by sensible distances; this can be shown by experiments.

Two cast-iron plates, called 'surface plates,' whose surfaces have been planed and scraped till they are as smooth as can possibly be, are placed the one on the other. When they are pressed together to exclude the air it is found that they adhere (Fig. 12) so firmly that they can support a considerable weight. That this is not due to atmospheric pressure, as with a boy's

[1] Unfortunately, practical men often use the word *strain* for *stress*.

sucker (HYDROSTATICS, p. 227), can be shown by suspending them under the receiver of an air-pump; the same weight is supported when the air is exhausted.

Graphite, the 'black lead' of which pencils are made, is reduced to fine powder and compressed. The particles are brought so close together by strong pressure that the molecular forces constrain them to form a solid mass. When machine shafting is revolving under great pressure, if lubrication is deficient, metal may strip off from the shaft or the bearing, owing to cohesion. This has occurred in the case of a vessel's screw shaft.

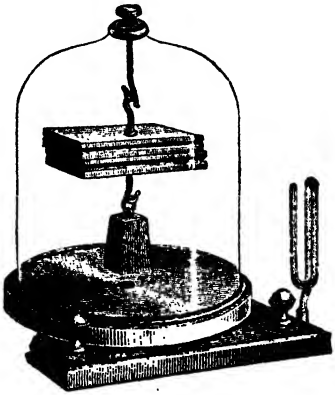


Fig. 12.—Adhesion of surface plates.

When metals are joined by soldering, brazing, or welding, the strength of the joint depends on cohesion.

Cohesion between parts of the same body is the cause of the strength of materials; this is classed under the heads *Tensile Strength*, *Crushing Weight*, and *Transverse Strength*, and is found in any engineering hand-book, such as Molesworth's *Pocket-Book*. Materials differ very much in their strength to resist elongation and compression. For example, cast-iron has a small 'tensile strength' and a large 'crushing weight,' while wrought-iron has a large 'tensile strength' and a small 'crushing weight.'

A light girder for carrying heavy weights may advantageously be constructed of cast-iron in the upper part, where it is subject to compression; and of wrought-iron in the lower part, where it is subject to tensile stress.

The molecular structure of bodies gives them a different capacity for withstanding both compressive and tensile stresses in different directions of the material.

Wrought-iron has a 'grain' which is similar to that of wood

Both wood and wrought-iron are stronger in the direction of the grain than across it.

Hardness of solids is their capacity for resisting scratching. It is usually measured by a scale of substances in the order of their power to scratch one another, beginning with the diamond, which is the hardest known substance.

SCALE OF HARDNESS.

10. Diamond	5. Apatite
9. Sapphire	4. Fluor-spar
8. Topaz	3. Calc-spar
7. Quartz	2. Rock-salt
6. Felspar	1. Talc

Hard substances are usually the most brittle or ready to disintegrate under blows, as explained in MECHANICS (p. 54).

Tenacity is the ability of a solid to withstand longitudinal stress, and is measured by the greatest force it can bear per unit of area without tearing asunder.

Wrought-iron has more tenacity than cast-iron; the most tenacious metal is steel pianoforte wire.

Rigidity is the capacity of a body to resist change of form—distortion. The coefficient of rigidity of a body is the quotient of the shearing stress by the distortion, measured by the change of one of its angles. The following values are given by Lord Kelvin in C.G.S. units.

Glass	150	Iron (cast)	542
Brass	350	Iron (wrought)	785
Copper	456	Steel (tool)	834

"If the earth as a whole were not more rigid than a ball of glass of equal size, the attraction of the moon and sun would pull it out of shape and raise tides on the surface" (*Kelvin*). Dr. Hecker of Potsdam estimates the rigidity of the earth at 676, and has measured the semidiurnal tide as 6 or 7 inches.

"**Elasticity** of a body is that property in virtue of which a body requires force to change its bulk or shape, and requires a continued application of force to maintain the change, and springs

back when the force is removed, and if left at rest without the force does not remain at rest except in its previous bulk and shape." This definition is taken from the article by Lord Kelvin on 'Elasticity' in the *Ency. Brit.*, which is an exhaustive treatise on the subject.

Compressibility and Tenacity are the qualities which combine to make a body elastic, two qualities which are observable in the very elastic substance india-rubber.

Fluids have no tenacity, so that they can only show elasticity when compressed. Liquids or gases are perfectly elastic in volume; in ordinary circumstances they regain their volume after compression, when the compressive stress is removed.

An air bed or cushion does not transmit any jar or concussion to a patient who is being carried on it, for any impact compresses the air and spreads the impulsive force over the whole area of the cushion. A pneumatic tyre acts in the same way, and prevents any jar from unevenness of the road.

In addition to showing elasticity when compressed, solids can also, in consequence of their tenacity, show elasticity when elongated.

In consequence of their rigidity, solids show elasticity of shear under Torsion and Flexure.

Elasticity of Torsion is the capacity which a rod or stretched wire has to recover its form after being twisted. The force resisting torsion varies as the angle of twist and the diameter directly, and inversely as the length.

Elasticity of Flexure is the capacity of a straight rod or plank to recover itself when fastened at one end and bent by applying a force at the other end.

In 1676 Hooke conducted a series of experiments on elasticity, the results of which he combined in the rule *Change of form is proportional to force causing it.* This law is the one which is perhaps unconsciously applied in most of our practical uses of Elasticity. Carriage springs, bows, spring balances, billiard balls are familiar examples of the use of elasticity, in which we rely on elastic bodies to exert a larger force, when there is more distortion.

Hooke uses the word 'force' for stress here, and it is almost impossible to avoid using it sometimes in that sense, inaccuracy being avoided by comparing the forces on the same area. The following useful experiment illustrates Hooke's Law, and also serves to impress on the mind the fact that stress is measured by force exerted per *unit* area.

Strips of vulcanised rubber $\frac{1}{2}$ inch (2 cm.) square in section, and about 2 ft. long, are provided with hooks at each end. They can then be stretched between two frames fitted with eyes, as shown in Fig. 13.

First, to illustrate Hooke's Law. One or two strips are

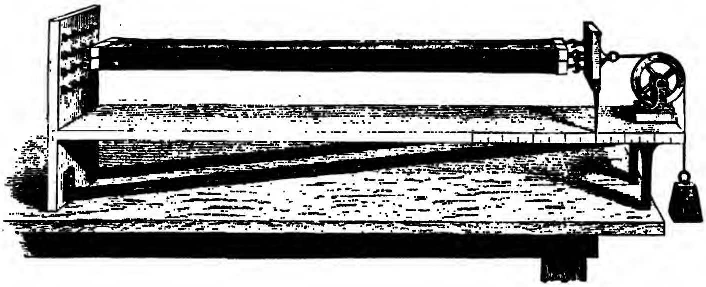


Fig. 13.—Illustration of tensile stress.

stretched by a weight of 1 lb. and the extension measured; another lb. is then added, and the extension is found to be twice the former, and so on, showing that extension varies as stress.

Secondly, to illustrate the measurement of tensile stress. If 1 lb. extends one strip one inch, 4 lb. will extend four strips 1 inch, and 9 lb. will extend nine strips 1 inch; the actual extensions are not of course even numbers, but are in these proportions. The four or nine strips may be bound together to make one strip, of which the sectional area depends on the number of the component strips. Such experiments clearly show that to produce a given deformation, a stress must exert a force proportional to the area.

Hooke's experiments tested the different kinds of elasticity:

(1) by a vertical rod stretched or compressed; (2) by a horizontal wire stretched by a weight in the middle; (3) by a horizontal plank fixed at one end and weighted at the other, (4) and with fixed ends weighted at the middle; (5) by a spiral spring extended by weights; (6) by a wire or rod fixed at one end and twisted at the other end.

These experiments tested elasticity of compression, elongation, torsion, and flexure.

A ball bounces in consequence of its elasticity. Two balls, one of steel and the other of glass, are allowed to fall on a smooth steel plate, which has been slightly greased; well-defined circles are marked on the grease (Fig. 14), showing that the balls have been compressed; their elasticity is shown by their recovery of shape. At the moment of impact the ball has a kinetic energy, and it does work through the distance by which the ball is compressed against the force which opposes compression. After rest, the elasticity of compression exerts a force through the distance of compression, which imparts an equal energy to the ball. The steel plate exerts the compressive stress on the ball.

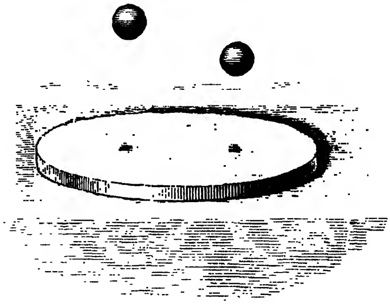


Fig. 14.—Bouncing balls.

The Limit of Elasticity is the greatest stress for which Hooke's law holds; if a greater stress be applied to a body, it either breaks or anyhow is incapable of regaining its original shape.

The Fatigue of Elasticity is a term invented to convey the fact that a long continuance in action of any stress or motion which changes the shape of a body will permanently alter its shape, even though the stress be less than the limit of elasticity. This may be called Viscosity of Solids. The internal arrangement of the molecules and their relative movements adjust themselves in accordance with the new conditions. The torsion

of a stretched wire is a form of elasticity very frequently made use of in scientific investigations. Lord Kelvin showed, from the behaviour of a wire, that changes of torsion caused by continued oscillation diminish the elasticity of torsion by one-half.

This alteration of molecular structure and cohesion affects the strength of materials, and the subject is full of interest to the engineer and mechanician, who are obliged to make provision for it in estimating the 'safe working load' of any structure. The strength of bridges and rails may be affected by the continued passage of traffic.

The subject cannot be further pursued, but one curious feature connected with it receives illustration in the following experiment, described by Lord Kelvin.

A wire stretched by a weight was twisted from a position of equilibrium through a quarter of a circle; after being kept in that position for six months, it was then twisted back past the position of equilibrium through a right angle in the other direction. When released, it first turned back nearly to its six months' position, and then very slowly began to turn back again to the original position of equilibrium, just as if it had a memory.

Solids only gradually regain their shape when distorted, and the time during which an impact, such as that of the glass and steel balls, lasts, can be measured with the aid of instruments of precision, and the compressions photographed and measured.

Both the forces and the intervals of time are finite quantities, and this must be borne in mind in connection with the subject of impulses treated of in MECHANICS, p. 34.

It is convenient to deal with the changes in momentum before and after impact instead of dealing with the forces, but momentum must not be considered as changed instantaneously.

The uses of elasticity are manifold. The main-springs and hair-springs of watches are substitutes for the weights and pendulum of the clock, and make it possible for the watch to go in any position, by substituting forces in any direction for the vertical forces of gravity.

Plasticity.—In so far as bodies are not *elastic* they are called *plastic;* they require force to change their bulk or shape, but they do not require a continued application of force to maintain the change, as they remain in the new shape. Bodies are elastic up to the limit of elasticity, and then they are plastic; and bodies are classed as elastic or plastic according as their limit of elasticity is large or small.

A bar of lead will vibrate, showing that it has elasticity, still lead has a small limit of elasticity, and is classed as a plastic metal.

For the matter of that, a piece of pitch will vibrate when struck; it has considerable tenacity, though it is classed as a viscous liquid.

Malleability is the capacity of a metal to endure being thinned out by hammering. It is a property which is possessed by metals to a varying degree, some of them, such as antimony, breaking up under the hammer. The property is much used in manufactures of the metals as follows:—

The thinness of gold-leaf has been referred to. Tinfoil is an alloy of lead and tin beaten thin. Tin-plate or block-tin is sheet-iron covered with tin. Zinc, silver, and copper are used in the sheet form, either hammered or rolled. Platinum-foil is used for electric batteries.

Malleable Cast-iron.—Iron castings may be made less brittle by heating them for some hours with black iron oxide.[a] During the process part of the carbon is removed from the cast-iron, so that it partakes of the nature of wrought-iron.

Ductility is the capacity of a metal for being drawn out into a wire through a draw-plate. Fine platinum wire has been mentioned. Silver, iron, copper, and gold are all well known in the form of wire; zinc and tin hardly ever. Lead, which is the most plastic of metals and is very malleable, is the least ductile.

Tenacity is the leading feature in ductility. Lead has the least tenacity of all metals, and it is the least ductile; aluminium bronze has a high tenacity, and it is on this account used for telegraph wires when a long span is necessary.

Steel wire of the highest class is the most tenacious, however, and so it is used in Sir William Thomson's sounding machine, where the wire is subjected to a very heavy stress,[1] as it is hauled in at a high speed.

When a solid is heated, the molecular forces are weakened, owing to the increase of molecular energy. In consequence, cohesion and those capacities which depend on it are diminished by heat. Plasticity is increased; metals are rolled and hammered into shape more easily when heated. At a temperature but little below the melting point glass and quartz can be drawn out into threads of extreme fineness.

Diffusion is the spreading of one fluid in another. The diffusion of gases affords the clearest proof of what has been described as 'the Kinetic Theory' of gases (p. 119). If two vessels, filled with different gases but at the same pressure and temperature, be placed in communication, the two gases will interpenetrate one another. Experiment shows that the rate of diffusion varies as the square root of the densities of the gases, thus supporting the Kinetic Theory. The theory explains the behaviour of gases as due to the rapid motion of translation of their molecules. Two gases being at the same pressure, the momentum of molecules crossing a unit of area is equal in both; the temperature being the same in both, the mean kinetic energy of their individual molecules is equal. It follows that the mean velocity of molecules in each is inversely proportional to the square root (of the mass of the molecules per unit of volume, that is) of their densities. Now the velocity of the molecules causes the diffusion, for the molecules are thus carried across the plane of separation, if no actual barrier exists; the rate of diffusion depends on the velocity of the molecules. Oxygen having sixteen times the density of hydrogen, the latter diffuses at four times the rate of oxygen.

[1] Any practical man would say 'strain' here.

N.B.—The inventions of Lord Kelvin, especially those invaluable to seamen, were universally known by his name, Sir William Thomson, before his elevation to the peerage.

When a gas at constant pressure escapes into a vacuum through a very small opening in a thin plate, the effect is called *Effusion*. This is another example which supports the Kinetic Theory. The rate of effusion varies inversely as the square root of the density, and this agrees with the theory as before.

The diffusion of liquids is less rapid. Some liquids, such as oil and water, do not mix at all; some, such as ether and water, mix only partially, in which case the lighter liquid mixed with some of the heavier, floats on the heavier liquid, mixed with some portion of the lighter. When salts of different kinds are dissolved in water, the spread of such solutions in water is an instance of diffusion. Graham conducted many experiments on diffusion by placing different solutions in equal glass jars, and allowing them to diffuse into equal vessels of water. When the new laboratory of Glasgow University was furnished, Lord Kelvin set up a long tube filled with water and with copper sulphate crystals at the bottom. This secular experiment on diffusion has been in process since the year 1870. The S. G. bulbs of Wilson (HYDROSTATICS, p. 209) are used to measure the concentration of solutions during the process of diffusion. Experiment here again supports the dynamical theory in showing that the rate of diffusion varies as the 'gradient of concentration,' that is as the change per unit of length in the quantity dissolved per unit volume. This was one of Graham's discoveries.

Colloids and Crystalloids.—Graham also divided substances with reference to their capacity for diffusion into *Crystalloids*, such as metallic salts, sugar, etc., which dissolve and diffuse easily; and *Colloids*, such as glue, gelatine, starch, etc., which dissolve and diffuse more slowly, and not in definite proportions, as is the case with Crystalloids.

Osmose.—If two liquids which will mix are separated by a membrane, diffusion takes place through the membrane, and is then called *Osmose*. Early observers had noticed that if a bladder be filled with alcohol and placed in water, the liquids mix through the bladder; the water passes more rapidly than alcohol through the bladder and bursts it. The rate of osmotic

diffusion varies with the nature of the liquid and also with the temperature. Osmose is confined to crystalloids, since colloids will not pass through a membrane; the two kinds of substances can be thus distinguished. Also a colloid and a crystalloid may be separated by placing the mixture in a membranous container, the crystalloid will pass through the colloid by diffusion, and then through the membrane. Jelly may be concentrated by putting it in a clean bladder or a wash-leather bag, when the water will ooze through the membrane.

There is also the passage of fluids through a porous diaphragm, such as unglazed earthenware; in the case of gases this is called *Atmolysis.* The term Atmolysis really means the separation of two different gases when the mixture is in contact with a porous container. The less dense gas passes through more quickly, the same rule applying as before, and the gases are thus separated.

Carbonic acid gas passes through the cast-iron of a stove, as referred to above (*Porosity*). This is by some classed as a chemical action, the gas combining on one side with the iron and being set free on the other; as may be the case with gas passing through an india-rubber division, or with the well-known instance of a soap bubble blown with carbonic acid. Here the action is probably chemical, and beyond the range of Physics.

HYDROSTATICS

CHAPTER I

Fluid Pressure

The Pressure of the Atmosphere—Torricellian Experiment—Pressure Varies with Depth—Fluid Pressure—Hydrostatics and Pneumatics—Pressure at a Point—Head—Measurement of Pressure at a Point—Vacuum—Manometers—Liquid Manometers—Standard Pressure.

The Pressure of the Atmosphere is the most widely extended of all fluid pressures, yet its existence was not suspected by the early philosophers, and its discovery has a personal history. Certain effects of the atmospheric pressure had been observed, but their causes had not been ascertained; for instance, that water rises to follow the plunger of a pump was held to show that 'Nature abhors a vacuum.' In 1642 the philosopher Galileo was appealed to for an explanation of the failure of some pumps erected in the gardens of the Duke of Tuscany. They were designed to draw water from a depth of 50 feet; the water rose about 30 feet, but would rise no higher; evidently Nature's abhorrence had its limits. Galileo seems to have indicated to his pupil Torricelli the probable explanation, but he died without being able to prove it. Torricelli, taking up the question, argued that if water rose to a height of about 30 feet, mercury, being $13\frac{1}{2}$ times as heavy, must rise to a height of about 27 inches. After trying the experiment with a plunger in a tube, he arrived at the experiment which is known by his name.

The Torricellian Experiment.—A glass tube closed at one end is filled with mercury and inverted in a basin of the same (Fig. 1). The mercury sinks in the tube until the height of the

column is about 30 in. above the surface of the mercury in the basin. This experiment, first conducted by Torricelli in 1643, seems to have carried conviction with it. The apparatus could be placed on a table and studied; here was a heavy column of mercury standing, to all appearance, unsupported. And when

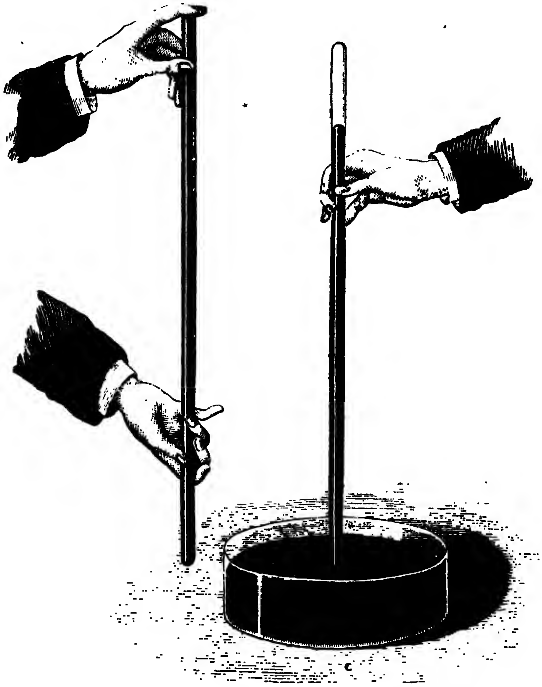


Fig. 1.—Torricellian experiment.

the reason for its so standing was studied, in what way did the surface of mercury inside the tube differ from the surface of mercury outside of it? Only in one feature, there was no air in contact with it. It must then be to the pressure of the air that the support of the column was due.

The pressure of the atmosphere was for the first time shown in the Torricellian experiment.

Pressure Varies with Depth.—The earliest observers saw that the cause of the pressure of the air must be the same as the cause of the pressure of water, viz. the weight of the fluid itself. Torricelli himself observed this, but he died in 1647, before he had the opportunity of submitting the problem to a test.

This test Pascal undertook. He carried the Torricellian tube to different elevations, and found that the length of the column of mercury supported by the atmosphere decreased as he ascended. In 1648 two observations were made by him, one of them at the foot of the Puy de Dôme, and the other at the top, a height of 3565 ft. The mercury column stood at 28 in. at the bottom and 24·7 in. at the top. Pascal then carried the tube down from the top and observed the mercury gradually rise, until it was equal in height to that in the tube which had remained at the bottom.

In this way the connection of the pressure of the atmosphere with its weight was clearly shown. And so in these six years three men in succession were found to continue this investigation on the other's death; and the philosophers of that and all succeeding time abandoned their old beliefs that the atmosphere extended to the moon, and that 'Nature abhors a vacuum.'

Fluid Pressure.—A fluid differs from a solid in this respect, that a perfect fluid offers no resistance to shearing stress, while a solid does. A perfect fluid can only exert pressure normal to any surface in contact with it. Water and air, the examples of liquid and gas most frequently met with and generally used in experiments, are not perfect fluids; they are to a certain extent '*viscous.*' Yet it is a matter of common experience that they mainly exert a direct thrust or pressure on a solid body. When diving into water, the hands should cleave the water and the body follow, without any part coming flat on the surface. Water offers a considerable resistance to any body meeting its surface flatly, little to a knife slicing through it. It is the same with air. The resistance offered by the air to a cyclist's motion much retards him; the 24-hr. record of G. Huret (1896) was made

behind a tandem with a wind shield, by which means the rider was relieved of the front pressure.

In Hydrostatics fluids are treated of as being perfectly 'mobile,' *i.e.* having no viscosity and exerting no sideways thrust on any surface, but only a normal pressure.

Hydrostatics and Pneumatics.—Fluids are of two kinds—liquids and gases; water is the familiar example of a liquid and air of a gas. Both air and water press against everything they touch, and this pressure is the only way in which they can exert force. Also, gravity excepted, pressure is the only form of force which can be exerted on them.[1]

For this reason, when a fluid mass is in equilibrium or when the forces which a fluid exerts on a solid are in equilibrium with other forces, the general conditions must be the same whether the fluid be a liquid or a gas. The study of these conditions is called HYDROSTATICS. The equilibrium of gases used to be studied under the name of Pneumatics (πνεῦμα, *pneuma*, a breath); Hydrostatics (ὕδωρ, *hydor*, water) being then the study of liquid equilibrium alone. There is an evident advantage in treating of them both together, as repetition is avoided.

Pressure at a Point.—However fluid pressure may vary from point to point in a fluid, there is at a point in it a definite fluid pressure. The intensity of the pressure at a point is measured by supposing pressure equal to it to be exerted uniformly over a unit of area—the force or thrust across unit area is called the pressure at the point.

Fluid Pressure is measured by the force exerted per unit of area.

For instance, the atmospheric pressure supports a column of mercury about 30 in. high in the Torricellian tube. If the internal section of the tube be one sq. in. in area, the pressure is equal to the weight of 30 cub. in. of mercury, about 15 lbs., on the sq. in.

Head is a convenient term for pressure due to or balanced

[1] Prof. Worthington's 'negative pressure' is included in this statement, though this is due to molecular forces, and therefore, not included in Hydrostatics.

by the weight of a liquid. For example, the atmospheric pressure is equal to '*a head*' of 30 in. of mercury or 34 ft. of water. The weight of 30 cub. in. of mercury or 408 cub. in. of water pressing on a sq. in. balances the pressure of the atmosphere on a sq. in.

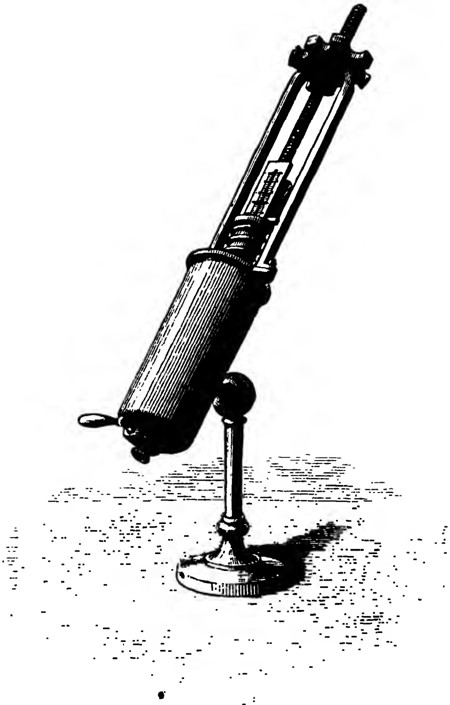


Fig. 2.—Pressure instrument.

In this chapter the fluid pressure is supposed to be uniform throughout the mass of fluid treated of. When this is the case the expressions—'the pressure on a fluid,' 'the pressure of a fluid,' and 'the pressure in' or 'at a point in a fluid' all have the same meaning,—are different names for the same pressure.

Measurement of Pressure at a Point.—In a fluid at rest the force exerted by the fluid pressure on any area in the fluid

is met by equal force in the opposite direction across the area. Consequently the pressure in any direction can only be perceived by removing all the fluid from one side of an area and measuring the force which the liquid exerts on the other side.

The instrument shown in Fig. 2 does this. Referring to the section of the instrument in Fig. 3, the piston A is made to fit truly to the end of the cylinder C, so that when the tap T is closed and A is at the end there is no space left there for any fluid. The whole apparatus being immersed in any fluid—*e.g.* air, water, or oil, so long as the tap is open the piston can be freely moved about in the cylinder, the friction being the force indicated on the spring balance B when the piston is moved either way by the screw S. The balance records no force due to fluid pressure, because this acts equally on both

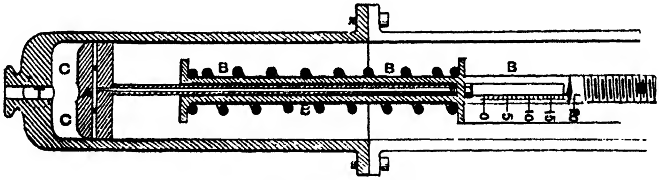


Fig. 3.—Section of pressure instrument.

sides of the piston. But when the piston A is at the end, and the tap is closed there is on the lower side of the piston no fluid and consequently no fluid pressure. Then, as the piston is moved by the screw S, the fluid pressure on one side of the piston is not opposed by other pressure, and the force which it exerts compresses the spring balance and is measured. The reading of the spring balance is taken as the piston is moved outward, then the screw S is reversed, and the force is read as the piston descends. The mean of these two forces is the product of the area of the piston and the pressure on it; the difference between the forces is due to the friction.

There is a ring of oil in the groove round the piston, which reduces friction and keeps fluid from entering the cylinder.

This instrument shows the pressure existing in any fluid.

It shows that at any point in the open air there is a pressure of about 15 lbs. on a sq. in., or a megadyne on a sq. cm., due to the *Pressure of the Atmosphere.*

Vacuum is an empty space; a space in which there is no air, vapour, or gas of any kind is said to be '*a perfect vacuum.*' The expression 'vacuum' is, however, used by engineers to describe a space which contains air or vapour at a pressure less than atmospheric pressure, and the expression needs explanation. The Torricellian vacuum at the top of a barometer tube is a perfect vacuum except for the mercury vapour, which has an inappreciable pressure at ordinary temperatures. If there is a perfect vacuum in a condenser A and it is connected with the top of a vertical tube BC dipping into a vessel of mercury C (Fig. 4), the mercury stands in the tube at a height of about 30 in. (76 cm.). A perfect vacuum is popularly said 'to support 30 in. of mercury,' or is called 'a vacuum of 30 ins.' Also if there is a pressure of air or vapour in the condenser due to 3 in. of mercury, the column, as shown in the figure, only stands at 27 in. There is then said to be 'a vacuum of 27 in.' or 'a vacuum supporting 27 in.,' and so on in the case of other pressures smaller than atmospheric pressure. Vacuum gauges are graduated in this way; the figures on the vacuum gauge D, reading from 0 to 30 in., give the height of the vertical column of mercury which the atmosphere would support in a tube communicating with the condenser or other vessel.

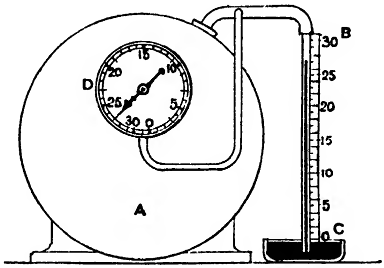


Fig. 4.—Vacuum gauge.

Manometers.—Instruments for measuring fluid pressure are called *Manometers* or *Pressure Gauges*, and they differ according to the amount of pressure which they are adapted to measure.

For the measurement of high pressures, such as those in

use in steam machinery, BOURDON'S PRESSURE GAUGE is employed.

Referring to Fig. 5; A is a cock in a small pipe connecting the gauge to the steam space in the boiler; B is a bent tube of elliptical section, as shown, one end of which is joined to the cock and the other closed and free to move. This free end works a sector D and pinion E by means of the connecting link C. D is pivoted at its centre, and E carries a pointer F which revolves with it.

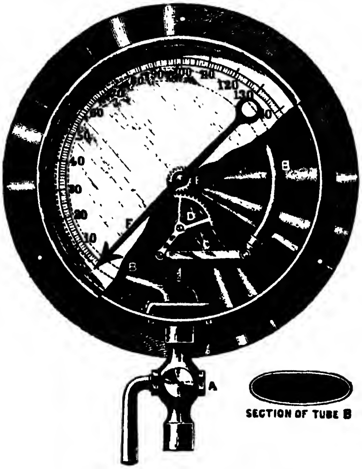


Fig. 5.—Bourdon's pressure gauge.

When the steam pressure within the bent tube increases there is a tendency in the tube to straighten itself, owing to the elliptic form throughout the tube tending to become circular under internal pressure; this causes the sector to move, and the pointer to indicate the pressure on a scale. This scale is graduated in lbs. on the sq. in. from readings of a standard gauge under the same pressure as the gauge itself.

A VACUUM GAUGE used for measuring pressures less than that of the atmosphere is in construction similar to a Bourdon's Pressure Gauge. The external atmospheric pressure causes the tube to become more curved as the internal pressure is reduced. It is graduated according to the column of mercury which would stand in a vertical tube communicating with the vacuum chamber.

AN ANEROID is used for measuring the atmospheric pressure at different times and places. It is described in connection with the subject of the atmospheric pressure (p. 221).

SAFETY VALVE.—In some sorts of safety valve the force exerted by a spring or the weight of a mass of metal resists the steam or water-pressure until it exerts a certain force, when the

steam or water escapes. A safety valve is a kind of pressure gauge, and the pressure of steam in a boiler may be measured by screwing up the spring until the steam is just escaping, when the force exerted can be read by the graduations. Or in the other form the weight P (Fig. 6) may be adjusted so as exactly to balance the force exerted by the steam on V; or the lever ACB of the safety valve may be treated like a Roman steel-yard (MECHANICS, p. 67, Fig. 35), in which the weight P is moved along the lever to balance the pressure.

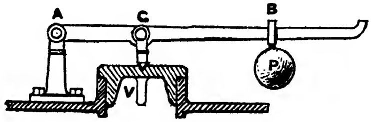


Fig. 6.—Safety valve.

Liquid Manometers are convenient because the liquid mass adjusts itself to the pressure. If there be liquid in a U-shaped tube, when there is more pressure on the liquid at one end than at the other, a column of liquid is supported whose weight per unit area of the tube is equal to the difference of the two pressures.

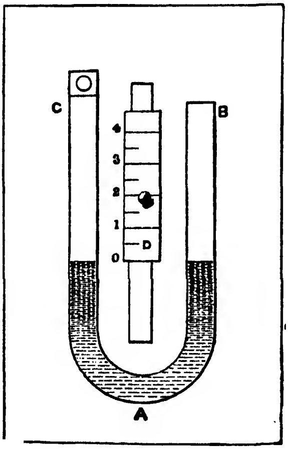


Fig. 7.—Air-pressure gauge.

Fig. 7 represents the AIR-PRESSURE GAUGE fitted in the stoke-holds of vessels using forced draught. Coloured water is put in the tube, B is open to the stoke-hold, and C to the open air. When there is pressure in the stoke-hold the water stands higher in AC than in AB, and the difference in the height is measured by the scale D, which slides. The air pressure is read off in inches of water. An air pressure of 3·5 inches is about 2 oz.-weight on the sq. inch.

MERCURY MANOMETERS.—Liquid Manometers used in experiments in Hydrostatics are usually filled with mercury, and by making a long enough vertical tube enormous pressures can be measured by a mercury manometer. In experiments conducted at the bottom of the St. Etienne mine

Amagat caused and measured pressures of 4000 atmospheres by means of a mercury manometer.

The weight of a cubic in. of mercury is ·49 lb.,[1] and of a cub. cm. is 13,333 dynes. These numbers give the measurement of pressure due to a unit column of mercury in lbs. per sq. in. and dynes per sq. cm.

SIPHON GAUGE.—Fig. 8 represents a liquid manometer or pressure gauge for measuring low pressures in the exhausted receiver of an air-pump. There is no air at A, the closed end of the tube, and the mercury is forced to the end by the pressure of the atmosphere. When the pressure is reduced at C, the

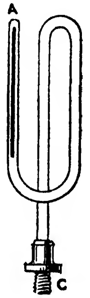


Fig. 8.—Siphon gauge.

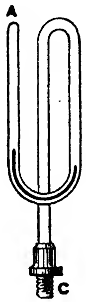


Fig. 9.—Siphon gauge; exhausted receiver.

mercury falls to the bend as in Fig. 9; the difference in height between the columns gives the head or pressure in the exhausted receiver.

Standard Pressure.—The atmospheric pressure varies at different places and times in various ways, which will be discussed later (Chap. VI.). It is convenient to use its mean value as a standard pressure, called an *Atmosphere.*

A column of mercury 29·922 in. (760 mm.) high is the accepted standard, *i.e.* the column of mercury which is supported in a Torricellian tube by the atmosphere when at standard pressure. The mass of this column of mercury of one sq. inch in section is 14·7 lbs., and of one sq. cm. in section is 1·0333

[1] Notice here the use of the 'force of one pound' (see MECHANICS, p. 50).

kilog. Its weight consequently exerts a force of 14·7 [1] lbs. on each sq. in., and (*at Paris*) 1,013,800 dynes on each sq. cm.—a pressure which is called an *Atmosphere.*

Since the weight of the standard column of mercury is different at different places it has been proposed to establish one million dynes per sq. cm. as the standard pressure of one atmosphere.

[1] See note on previous page.

CHAPTER II

Laws of Fluids

Laws of Fluids—Pascal's Principle—Upward Pressure—Transmissibility of Fluid Pressure—Hydrostatic Paradox—Hydrostatic Bellows—Hydraulic Press—Transmission of Hydraulic Power—Accumulators—Escape Valves—Hydraulic Engines—Transmission of Power by Air Pressure.

Laws of Fluids.—There are three fundamental principles of Hydrostatics, which we may call the *Laws of Fluids*.

I. Fluid Pressure is normal to any surface exposed to it.

II. Fluid Pressure at a point in a fluid at rest is of the same intensity in all directions.

III. Fluid Pressure is the same at all points in a fluid mass, neglecting the weight of the fluid.

The first of these laws is a consequence of the nature of 'a perfect fluid,' which is perfectly mobile and unable to withstand a shearing stress. A perfect liquid cannot exert a side-ways thrust on any surface, that is a thrust any part of which is parallel to the surface.

This principle has been described and illustrated in what has gone before.

The second is called **Pascal's Principle** of the Equality of Fluid Pressure in all directions. It is capable of mathematical proof from the nature of a perfect fluid.

It can be also illustrated by experiments.

1. If an empty bottle be corked and weighted so as to sink and then be lowered into deep water the cork will be forced in,

and this is equally the case whether the bottle be upright or inverted or on its side.

2. The instrument described on p. 154 (Fig. 3) is mounted on a ball and socket joint, so that it can be turned to face in any direction. This instrument actually measures the pressure normal to the outer face of the piston. This pressure is seen to be the same in whatever direction the instrument is faced, showing that the intensity of the pressure at a point is the same in every direction.

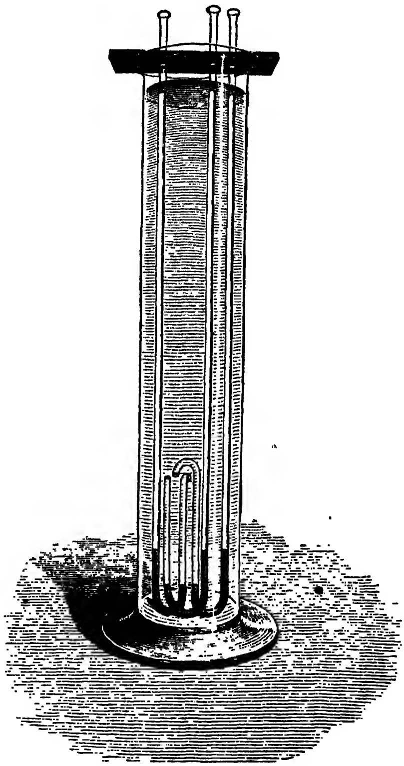


Fig. 10.—Pascal's principle.

3. Several U-tubes with a long and short arm have the opening of the shorter arms fashioned to open in different directions,—upwards, downwards, and sideways, the bend of the tubes containing an equal amount of mercury. The tubes are lowered into a tall vessel of water (Fig. 10), and their openings are all brought as nearly as possible to the same point. The column of mercury stands in each at the same height, showing the pressure at the point to be the same in every direction.

4. A plunger works freely in a glass cylinder opening out into a globe. At different parts of this globe are short tubes which open in all directions (Fig. 11). If the globe and

cylinder be filled with liquid, when the plunger is pressed in the liquid spirts *equally* from every hole, showing the pressure to be equal in all directions.

This experiment illustrates the third Law of Fluids rather than the second, as it shows the pressure exerted by the plunger to be equally transmitted throughout the fluid.

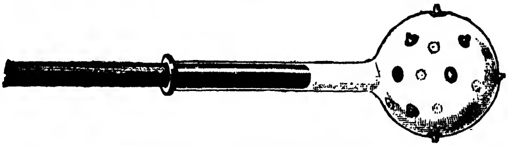


Fig. 11.—Pascal's principle.

Small U-tubes containing mercury are sometimes fitted instead of mere holes; then the apparatus may be filled with air or gas, showing the pressure in gas as well as in liquid to be equal in all directions; or if filled with liquid the equality of pressure is measured instead of making the liquid 'spirt equally from the holes,' which is a little vague.

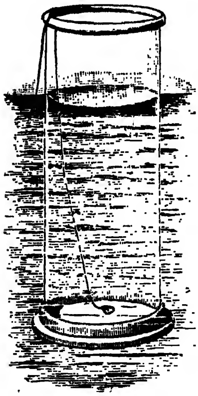


Fig. 12.—Upward pressure.

Upward Pressure.—Experiments are devised to show the upward pressure of fluid.

The lower end of a glass tube about 2 in. (5 cm.) diameter is ground flat, so that it may be closed by a flat brass plate.

At the centre of one side of the plate is a ring or hook, and if a string be fastened to the hook and passed through the glass tube, the plate can be kept against the end which has been ground flat.

The tube thus closed is plunged into water, and so long as the top is kept above the surface no water will enter (Fig. 12). The string may then be left loose and yet the plate will not fall off; the fluid exerts on the plate an upward force greater than its weight.

If a similar glass tube closed at one end by a bladder or a

piece of rubber be plunged into water, the membrane is pressed upwards by the liquid.

The expression 'upward pressure' is often used, but it is misleading. The pressure at a point is as much upward as downward and equal in every direction, and a fluid exerts an equal force normal to a small area in whatever direction the normal may be.

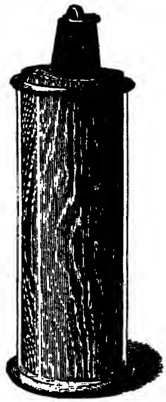


Fig. 13.—Pressure on a solid.

Transmissibility of Fluid Pressure.—Supposing that a cylinder of wood be made to fit easily in a tall vessel and pressure be applied on the top by placing a piece of lead on it (Fig. 13), the weight of the lead exerts a force through the wood on the bottom of the vessel. This is the only force which the pressure exerts on the vessel, and it is equal to the weight of the lead and wood.

But now suppose that, instead of the piece of wood, there had been water in the vessel and a flexible water-tight cover on it (Fig. 14). If the lead be placed on the cover, its weight not only exerts an equal force on the bottom but also exerts pressure at every point of the side of the vessel.

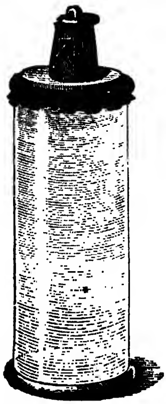


Fig. 14.—Pressure on a fluid.

This illustrates the difference between pressure of one solid on another, which is a force in one definite direction, and fluid pressure, which is the same in every direction. Excluding the weight of the water, there is the same pressure at every point of the water in the vessel; its intensity is measured by the weight of the lead divided by the number of units of area in the cover, and this pressure is exerted at every point of the sides and bottom of the vessel normal to the surface there.

Owing to the transmissibility of pressure any force impressed on a fluid is multiplied.

Hydrostatic Paradox.—If a closed vessel with plane sides be filled with fluid, and force be exerted on a small surface of the fluid, a force of equal magnitude is exerted on every equal area of the sides, and the force is thereby multiplied. In popular language, force, work, and power are not clearly distinguished, so that force is often confused with work. Now work and power cannot be increased by mechanical arrangements; and so it is considered paradoxical that force should be multiplied by the agency of fluid in a machine.

Fig 15.—Hydrostatic bellows.

The Hydrostatic Bellows.—Two circular discs of wood are connected by a waterproof canvas cylinder forming a collapsible drum which will hold water (Fig. 15). To the lower disc is fastened a brass tube of small section which communicates with the inside of the drum. The brass tube has cemented on to it a glass tube and funnel standing vertically, and the drum is filled with water. Weights placed on the bellows cause the water to rise in the tube.

The head of water in the tube causes a pressure which impresses force on the water in the drum at the small area where the tube opens into it. This force is exerted on every equal area of the top disc, so that the water exerts a very great force on this disc, which will support a great weight. A man may stand on the bellows and his weight be supported by a mere thread of water. This is the Hydrostatic Paradox:—*A very small amount of water can be made to support any weight, however great.*

It is customary to describe an experiment in which a cask placed on end is filled with water and a small tube inserted in the head of the cask is led to a great height and also filled with

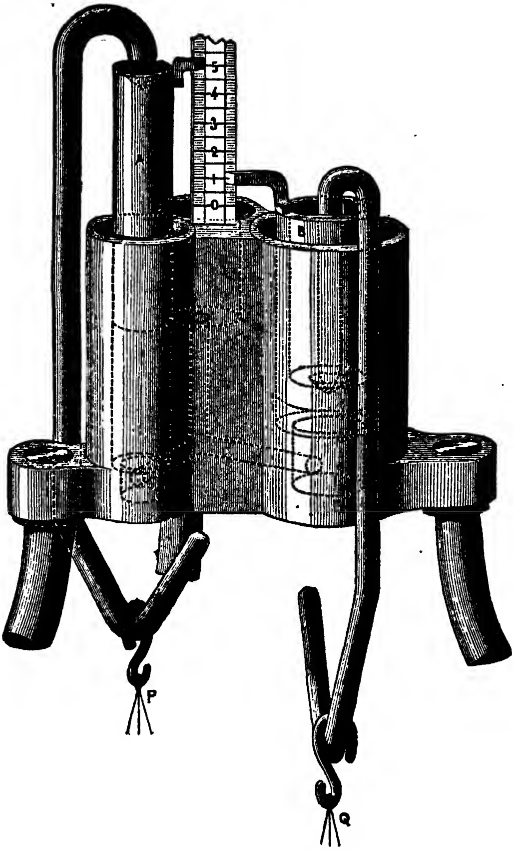


Fig. 16.—Hydrostatic paradox.

water. Here a small amount of water in the pipe should, in theory, exert such an enormous pressure on the cask as to burst its iron hoops. Experiments conducted on the upper deck of H.M.S. *Britannia* with an iron gas-pipe led up the foremast always caused great disappointment. The soundest cask leaked

so much under pressure that the column of water never stood high enough in the tube to give the pressure necessary to burst it.

The instrument shown in Fig. 16 is designed to illustrate the hydrostatic paradox, and to prove the transmissibility of fluid pressure. The piston A, diam. 1 in., and the piston B, diam. 2 in., both rest on fluid in cylinders which they fit closely, and which are joined by a tube. Force impressed on the pistons causes pressure in the fluid. The face-area of the piston B is four times that of A, and so whatever force is impressed on A must be exerted fourfold on B if the fluid transmits the pressure equally to all parts. This is seen to be the case; 1 lb. suspended as P and resting on A supports 4 lbs. suspended as Q and resting on B. Neglecting friction a weight of 1 lb. raises a weight of 4 lbs., which is 'a paradox.'

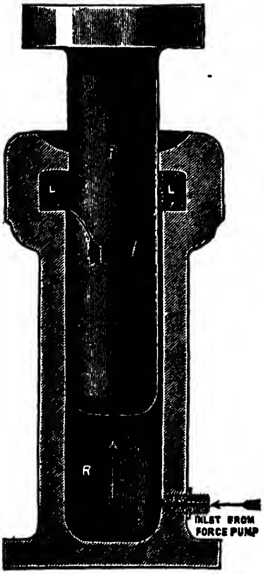


Fig. 17.—Bramah press.

An index on each piston shows its rise and fall on a scale; A is seen to move four times as much as B. The Principle of Work (MECHANICS, Chap. VI.) applies to this simple hydraulic machine. The work done *on* the machine by P in moving A through 1 in. is equal to the work done *by* the machine at B in moving Q, which is four times P, through $\frac{1}{4}$ in.

The Hydraulic Press or Bramah Press in one of its many forms is used to exert a great force. A strong piston or 'ram' P works in a very strong cylinder R (Fig. 17). A pipe communicates with the small cylinder of a force-pump with a piston Q, not shown, but of a similar shape to the ram. The ram P usually has an area many times that of Q, and any force impressed on Q is transmitted to each equal area on P; the press

exerts a force that number of times the force applied to the piston of the pump. A man applying a moderate force on the pump-piston Q can exert a very large force by means of the ram P.

The Principle of Work applies to this as to other machines. The work done on the pump is equal to the work done by the press. The piston speed of the pump bears to the piston speed of the ram the same ratio that the area of the ram does to that of the pump.

In order to avoid leakage between the ram of the press and the cylinder under very high pressure, the *cup leather* invented by Bramah is used. It consists of a circular piece of stout leather, saturated with oil so as to be impervious to water. A large central circular hole is cut in it; it is then bent, so that a section of it, seen at L, is like the letter U, and it is fitted into a groove made in the neck of the cylinder R. This collar being concave to the pressure, fits more tightly against the ram P on one side and the cylinder on the other side as the pressure increases. The ram of the press can move freely, but the water cannot escape.

Transmission of Hydraulic Power.—The transmissibility of pressure is used to transmit power. In Hull, London, Liverpool, Melbourne, Birmingham, Sydney, Antwerp, Manchester, and Glasgow, naming the places in the order in which the system was adopted, pipes are laid under the streets, and water under pressure is pumped into them from a central station. In London the pressure is 750 lbs. on the sq. in., in Glasgow 1120 lbs. on the sq. in. This pressure is transmitted in 7-in. pipes to all parts, and customers can apply it to operate the hydraulic rams of lifts, cranes, or machines as required. Ten million gallons of water are pumped into the London mains in a week, and any visitor to the various docks in the port of London can see the cranes worked by this invisible power.

Accumulators.—The enormous pressures referred to above are maintained in the supply pipes by pumps. Now the amount of water power used by customers varies from time to time, and

it might be that all ceased to use it at the same moment. To avoid the impulsive stress on pumps and pipes which a sudden stoppage of the water under such pressure would cause, an accumulator is used. This has a long plunger P, like the ram of an hydraulic press (Fig. 17), loaded with a mass M, whose weight, divided by the horizontal area of the plunger, is equal to the pounds per square inch of fluid pressure maintained in the pipes. When the water is not used, the work of the pumps is expended on lifting the ram and mass M, while the pumps gradually come to a standstill. The accumulator meanwhile maintains a pressure in the pipes ready for use. The Glasgow accumulators have rams 18 in. diameter and 23 ft. stroke, each loaded to 127 tons.

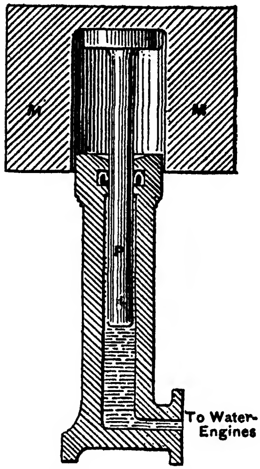


Fig. 18.—Accumulator.

Escape-Valves.—It is often impossible to fit accumulators, *e.g.* in steam-vessels the arrangement could not be made. In this case escape-valves are provided. These are like the valves on a boiler, controlled by springs screwed down to a pressure a little above the working load. When the hydraulic presses for which the pressure is provided cease working the pressure rises throughout the whole mass of water, and becomes greater than the pressure exerted on the valves by the springs. Water escapes gradually, and undue strain is avoided.

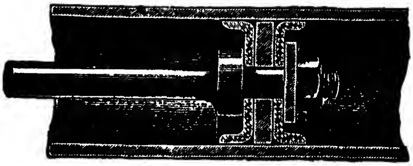


Fig. 19.—Double cup-leather.

Hydraulic Engines.—The transmissibility of pressure is utilised in hydraulic engines. These have pistons somewhat similar to those of steam-engines,

but the pistons are fitted with double cup leathers (Fig. 19) to avoid leakage under the high pressures used. The conditions of effective working are more appropriately discussed under the heading of 'Moving Liquids,' p. 254.

Transmission of Power by Air under Pressure.—Compressed air is used for actuating motors; for instance, the tramways in Berne are on that system. One difficulty which has to be met is explained on p. 276; the air, expanding in doing work, cools, and, unless artificially heated, causes a thick layer of snow to be formed at the exhaust. In Birmingham, pipes were laid and all arrangements made for the transmission of power to small workshops by compressed air. But the company failed because of that and other practical difficulties.

Pneumatic tools, such as drills, riveting hammers, fullers, etc., contain small motors driven by compressed air fed to them by flexible pipes.

In speaking of the transmissibility of fluid pressure the weight of the fluid has been neglected. In such practical uses of fluid pressure as have been referred to, pressures due to the weight of the fluid mass are insignificant compared with those due to the impressed forces. Except in such circumstances, the weight of a fluid mass must be taken into consideration, as the pressure at a point in a fluid is in most cases due to the weight of the fluid alone.

CHAPTER III

Liquid and Gas

Compressible Fluid—Incompressible Fluid—Boyle's (or Marriotte's) Law—Boyle's (or Marriotte's) Tube—Deep Trough—Voluminometer—Simple Air-Pump—Smeaton's Air-Pump—Double-barrelled Air-Pump—Tate's Air-Pump—Sprengel's Pump—Topler-Hagen Pump—Exhibition of Atmospheric Pressure—Magdeburg Hemispheres—Shrivelled Apple—Mercury Rain.

If a thick glass tube with even bore, provided with a well-fitting plunger (Fig. 20), be filled with fluid, force exerted on the plunger causes pressure in the fluid. Fluid, whether liquid or gas, exerts pressure on any surface in contact with it; but the effect of pressure on a gas is very different from its effect on a liquid.

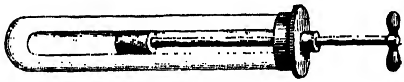


Fig. 20.—Pneumatic syringe.

Compressible Fluid.—If the fluid be air or any gas the effect of the pressure in the fluid is to diminish its volume considerably, the air is compressed. When the force is removed, the pressure in the air is lessened, and the air expands. Gases, of which air is taken as the general example, are called '*compressible*' fluids. They are sometimes incorrectly styled 'elastic' fluids; all fluids are elastic (see Properties, p. 139).

Incompressible Fluid.—If the tube (Fig. 20) be filled with water the effect of force applied to the plunger is very different. In this case the fluid does not, so far as can be seen, yield at all,

but resists compression almost perfectly. It is on this account that liquids are called '*incompressible*' fluids.

What has been said under the heading of Compressibility (PROPERTIES, p. 135) should be referred to. Water is compressible and elastic, but the two experiments just described show how very easy it is to compress gas, and how very difficult to compress liquid. So long as it is borne in mind that in reality all fluids are compressible and almost perfectly elastic, there can be no mistake in speaking of gas as '*compressible*' and liquid as '*incompressible*' fluid. The use of the expressions is justified by ordinary experience.

Liquids, of which water may be taken as the common example, maintain a constant volume. The use of liquid measures depends on this; a quart, a litre, a gallon of a certain liquid are definite masses. The easily remembered rule, 'a cubic foot of water weighs 1000 oz.' is nearly true, because 1000 oz. of water neither swells nor shrinks perceptibly, but always occupies about one cubic foot.

When measuring a quantity of gas by its cubic contents the pressure of the gas must also be stated. It is not correct to say that a litre of air weighs 1·3 gramme; it must also be stated that the air is at atmospheric pressure. If the pressure in a litre of gas were decreased there would be less gas, and if there were no pressure there would be no gas.

It is at atmospheric pressure that air and gases are usually measured.

Boyle's (or Marriotte's) Law.—That the volume of a given mass of gas depends on the pressure in it was discovered by the Hon. Robert Boyle. In 1660 he published some *New Experiments touching the Spring of the Air*, from which he derived the law which is known as Boyle's Law. In 1679 Marriotte published the same law with the same experiments as an independent discovery: the law is known on the Continent of Europe by the name of Marriotte.

Boyle's (or Marriotte's) Law in its modern form is: *If the temperature be constant the volume of a gas varies inversely as its pressure.*

Boyle's (or Mariotte's) Tube.—A glass U-tube has a shorter and closed arm about 6 or 8 in. (20 cm.) long, and a longer open arm 36 in. (90 cm.) long (Fig. 21), and is mounted on a vertical board. The shorter arm is graduated on the glass in equal volumes from the closed end, divided in the figure into five equal parts. Clean mercury is poured into the bend and when the surfaces of mercury in both arms are level, the air enclosed in the shorter arm is at atmospheric pressure. Its volume is read off by the graduations, and then additional mercury is poured into the open end, causing additional pressure on the enclosed air which diminishes in volume. A scale is provided for reading the height of the column of mercury in the longer arm above the surface of mercury in the shorter arm. When the volume of the confined air is half of what it was at atmospheric pressure, the height of the column of mercury above the free surface is equal to the height of the barometer. This shows that the air is at a pressure of two atmospheres when its volume is half what it was when at a pressure of one atmosphere.

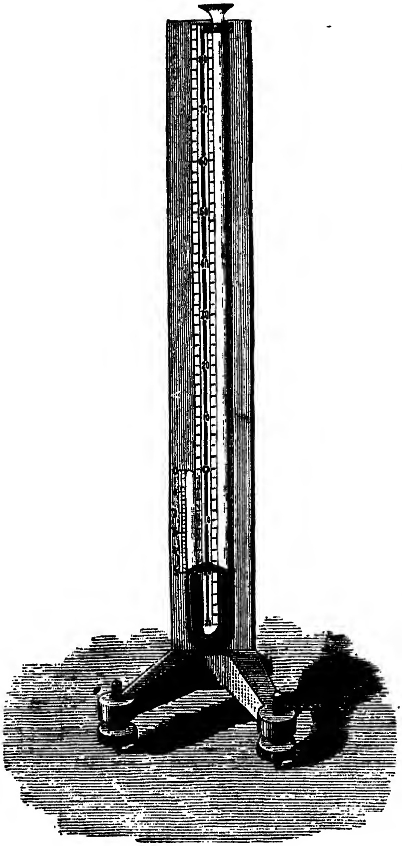


Fig. 21.—Boyle's tube.

Experiments may be further made with Boyle's tube by noticing the volume of the confined air when the pressure is

between one and two atmospheres. The volume of the confined air is inversely proportional to the pressure. For example if the column of mercury in the longer arm be 10 in. (253 mm.) above the free surface, giving an additional pressure of $\frac{1}{3}$ atmosphere, the volume of air at $\frac{4}{3}$ atmospheric pressure is $\frac{3}{4}$ of what it was at one atmosphere.

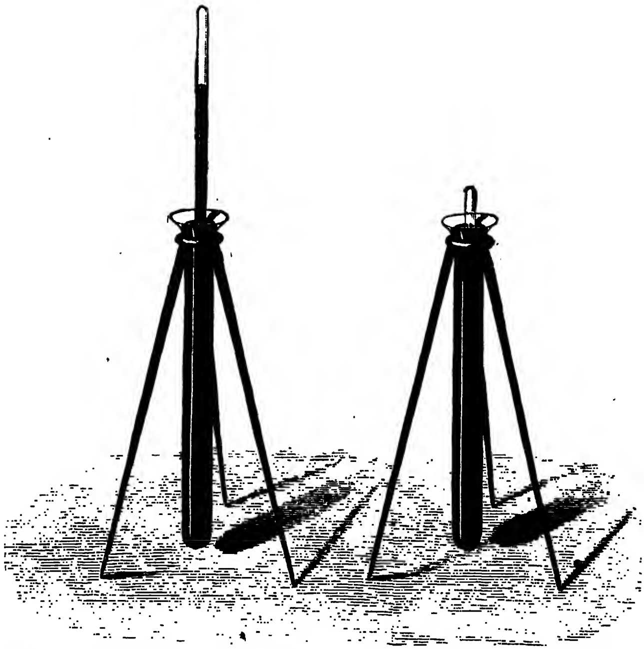


Fig. 22.—Deep trough ; pressure reduced. Fig. 23.—Do. ; atmospheric pressure.

Deep Trough.—A different apparatus is employed to show increase of volume in air when its pressure is less than one atmosphere.

A strong glass tube about 32 in. (90 cm.) long and 2 in. (5 cm.) internal diameter, closed at one end, called a *Deep Trough*, is filled with mercury. A smaller straight tube about 30 in. long closed at one end is filled with mercury all but about 4 in., and being inverted is sunk into the deep trough until the

mercury inside and outside the tube is at the same level (Fig. 23). The upper part of the smaller tube remaining above the mercury is graduated on the glass in equal volumes from the closed end; this now contains 4 in. of air at atmospheric pressure.

As the smaller tube is raised the mercury recedes from the closed end, showing that the air in it expands; but the mercury stands in it above that in the trough, showing that the pressure is decreased (Fig. 22). When the confined air has expanded to twice its original volume and occupies 8 in. (20 cm.), the column of mercury stands about 15 in. (38 cm.) above the mercury in the trough. If there were no air and no fluid pressure on the top of this column it would stand about 30 in. above the surface, as in the Torricellian experiment (p. 150), also when the mercury surfaces were level, as at the commencement, the confined air was at atmospheric pressure; we therefore conclude that when the volume of the confined air is doubled the pressure on it is halved. By choosing various positions of the small tube it may be shown that the volume of the confined air varies inversely as the pressure on it.

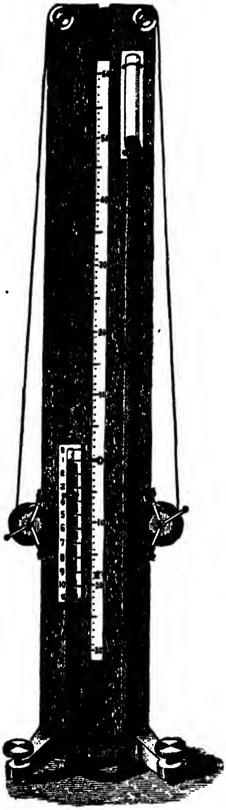


Fig. 24.—Voluminometer air compressed.

Voluminometer (*Measurer of volume*). Experiments of both kinds can be carried out with one apparatus. Two glass tubes, the one (A) open and the other (B) closed, are connected by a strong rubber pipe. The closed tube is graduated on the glass in equal volumes from the closed end. The tubes are both placed vertically on a frame provided with a vertical scale which can be moved up and down (Fig. 24). The glass tubes and the flexible tube are filled with mercury so as to enclose about 3 in. of air in the closed

tube when the surfaces of mercury in both glass tubes are level, that is when the confined air is at atmospheric pressure.

As the tubes are to be raised and lowered and the weight of mercury is considerable, it is convenient for the instrument to have windlasses to wind up and hold each tube as required. In Fig. 24 B is shown lowered and A raised, so that the mercury in A stands at twice the barometric height above the mercury in B; the pressure of the confined air is then 3 atmospheres and the air that occupied 3 in. at first is compressed into $\frac{1}{3}$ the former space, *i.e.* 1 in.

On the other hand, the tube B can be raised and A lowered so that the mercury in A stands at a fraction of the barometric height below that in B; the volume of the confined air is increased. In Fig. 25 the volume is increased threefold, to 9 in. In that case the mercury in A is about 20 in. below the level of the mercury in B.

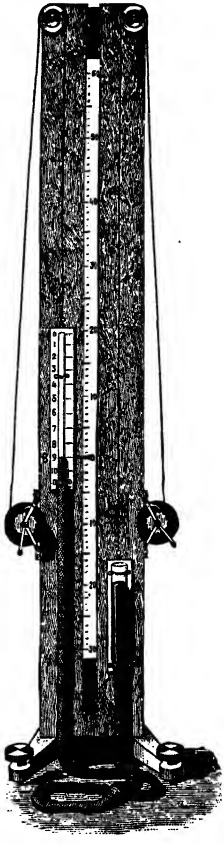


Fig. 25.—Voluminometer air expanded.

The behaviour of gases known as Boyle's Law may be expressed by saying that, temperature being constant, the product of pressure and volume is a constant quantity. This is practically true of those gases which are difficult to liquefy by compression—air, hydrogen, etc. But strictly speaking in all gases, as the pressure increases, this quantity diminishes to a minimum value, and then increases (see HEAT, p. 327).

The Simple Air-Pump.—Air expands into and completely fills any empty space. If a vessel full of air be opened into an equal empty one, the air fills both of them, and its pressure is halved. A cylinder with a closely fitting piston, which can be

drawn away from the closed end, forms such an empty vessel, and if a reservoir full of air be connected with it the air will expand into and fill the cylinder as the piston is drawn away. The return of the piston would compress the air into the same space again, but a valve or door A (Fig. 26) is fitted at the bottom of the cylinder, and prevents the return of the air into the reservoir, while a valve B in the piston allows the air to escape through the piston as it returns to the closed end. As the operation is repeated the air in the reservoir is rarefied until its pressure will not lift the valve A.

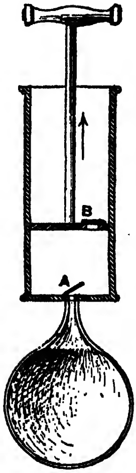


Fig. 26.
Simple air-pump.

There must be a little space at the closed end when the piston is close home; this space is usually called 'the clearance.' The valve B in the piston will not open on the down stroke until the air at the bottom of the cylinder is at atmospheric pressure, so whatever space is left at the bottom of the cylinder must contain air at that pressure. This sets a limit to the exhaustion of the receiver; the ratio of the clearance to the whole volume of the cylinder will be the minimum fraction of the atmospheric pressure in the reservoir. The pressure in the reservoir will not lift the valve A unless it is greater than the pressure of the air remaining in the cylinder when the piston is furthest from A.

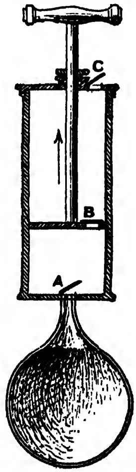


Fig. 27
Smeaton's air-pump.

Besides this defect, since the atmosphere presses on the piston and is opposed by a smaller pressure on the other side at every stroke, this simple pump is tedious to work.

Smeaton's Air-Pump is the same as a simple air-pump, but the other end of the cylinder is closed and has a valve C opening

outwards (Fig. 27). When the piston is raised the air above it is forced out through this valve, and the air from the reservoir lifts the valve A and fills the space below the piston. When the piston is lowered the valve B in the piston is raised and allows the air to pass through to the other end. The operation is repeated and the air in the reservoir is rarefied until it does not provide sufficient force to lift the valves.

The air in the cylinder is rarefied continuously and the exhaustion in the receiver is more complete than with the simple

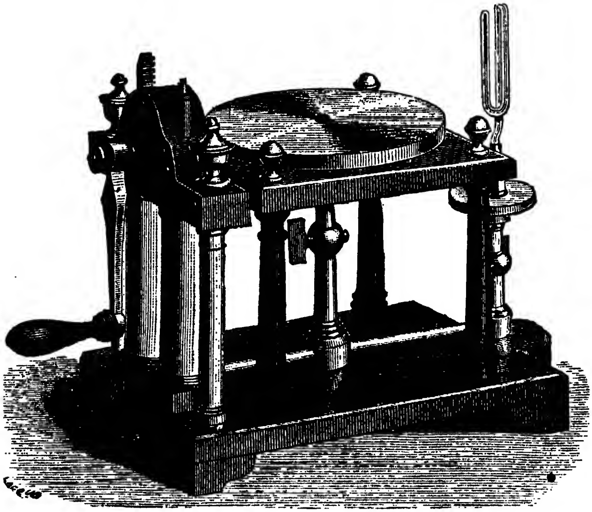


Fig. 28.—Double-barrelled air-pump.

air-pump. Smeaton's air-pump is also easier to work, because the pressure of the atmosphere is prevented by the valve C from exerting force on the upper part of the piston.

The Double-Barrelled Air-Pump is usually employed because the exhaustion is twice as rapid.

Two cylinders are seen on the left in Fig. 28; the rods which move the pistons in them project above the woodwork, and are made with a toothed rack operated by a pinion, to which a handle is attached. As the handle is worked to and fro, one

piston rises and the other falls. The two circular horizontal plates are perfectly flat and smooth; glass domes called 'receivers' are placed on them, as requisite, to be exhausted; or any apparatus from which the air is to be removed may be screwed into the central holes. Each plate can be connected with or cut off from the pump by a tap. A siphon gauge is shown screwed into the hole of the smaller plate.

Tate's Air-Pump has two pistons, as shown in the broken cylinder (Fig. 29); a single block piston, a little less than half the length of the cylinder, is also used. When the pistons are

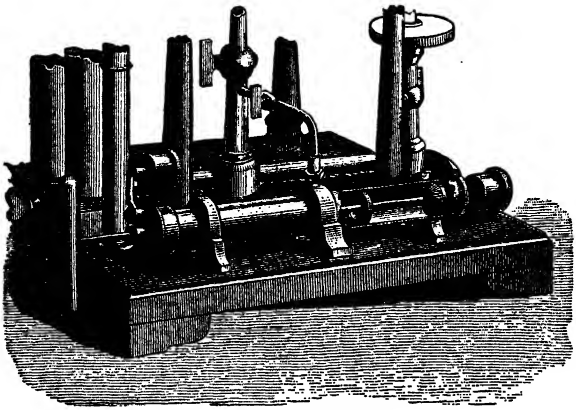


Fig. 29.—Tate's air-pump.

as shown and the taps are open, air expands from the reservoir into the nearer part of the cylinder; the handle is then drawn out and the pistons come to the nearer part of the cylinder; this air is expelled through the valve in the nearer valve-box, while at the same time air expands into the further part. The air in the reservoir has not to lift any valves, and there is no valve in the piston to be lifted, consequently the exhaustion is more complete. At the end of the stroke 'the clearance' always contains air at atmospheric pressure, so the ratio of the clearance to the whole volume of the reservoir is the limit of exhaustion. Tate's air-pump is often used as

auxiliary to another kind of air-pump, which exhausts more rapidly at first but does not exhaust so perfectly. In the figure it is shown in this way, fitted as an addition to the double-barrelled air-pump (Fig. 28).

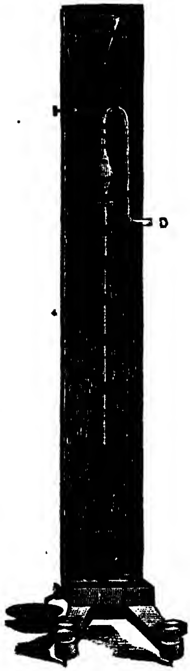


Fig. 30.—Sprengel's air-pump.

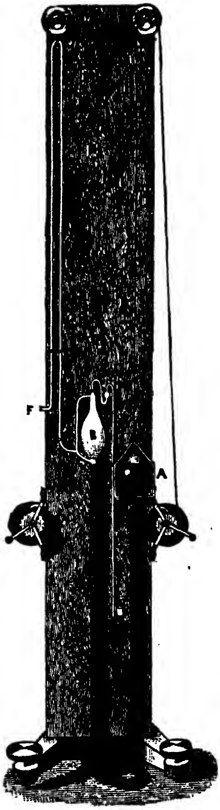


Fig. 31.—Topler-Hagen pump.

Sprengel's Pump.—The air-pumps which have been described have each of them a limit of exhaustion, because pressure is necessary to lift their valves. If a higher rarefaction is desired, mercury pumps are used. The space left at the top of a barometer tube, called 'a Torricellian vacuum,' only contains

the mercury vapour corresponding to the temperature. It is the object of Sprengel's pump to attain to this condition in the exhausted reservoir. A common form of this pump is shown in Fig. 30. The mercury in the funnel A falls down the vertical tube BC in drops, and carries with it the air which expands from the reservoir through the pipe D into the space between the drops. The exhaustion proceeds rapidly, until the drops as they fall into the basin sound hard and solid, when the air no longer cushions between them. This is a simple and effective pump, and the figure shows some modifications suggested in it by experience. BC must be considerably more than the barometric height, say 45 inches.

Topler-Hagen Pump.—A reservoir of mercury A is suspended by a band worked by a ratchet-barrel, and it is connected by a stout rubber pipe with the tubes at K (Fig. 31). When A is raised the mercury flows into the bulb B, and since the outlet C is sealed by the mercury, any air in B is driven out through the siphon E as mercury pours into it from B. When A is lowered the mercury falls below C, and air is free to come from the reservoir through the inlet F. The by-pass tube D is provided as a guard against breakage from the sudden rush of air from F directly C is free. As the exhaustion becomes complete, the mercury will stand nearly at the barometric height in CG when A is raised, and in EH when A is lowered, and so both of these vertical tubes must be longer than 30 in. (76 cm.).

Exhibition of Atmospheric Pressure.—With the aid of the air-pump many experiments may be made to prove the existence of atmospheric pressure by observing what occurs when it is removed.

Fig. 32.—Bursting of bladder.

A glass vessel whose lower rim is ground flat is covered on the top with bladder tightly stretched over the edges. The lower edge is smeared with lard, and so fits firmly on the plate of the air-pump (Fig. 32). When

the air is exhausted from the space under the bladder the downward pressure of the air above it is no longer balanced by the upward pressure below it.

The atmospheric pressure makes itself apparent, pressing on the bladder until, unable to withstand the strain, it bursts with a loud report.

Magdeburg Hemispheres.—Two hollow hemispheres fit closely at their edges. If the air be exhausted from the hollow sphere thus formed, the pressure of the atmosphere on the outside is no longer balanced by the pressure inside. Great force is necessary to separate them. Otto von Guericke, Burgomaster of Magdeburg, had two such hemispheres made about 3 feet in diameter. As he had not yet invented his air-pump he filled

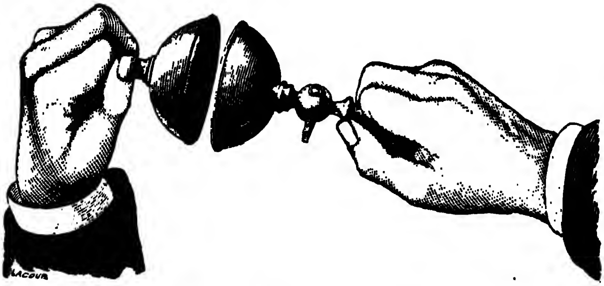


Fig. 33.—Magdeburg hemispheres.

them with water, and then drew the water out with a common pump. When exhausted they were held together by a force of some $6\frac{1}{2}$ tons, and resisted the efforts of twenty of the Emperor's coach-horses to separate them.

The experiment is now performed with lecture-room apparatus, the hemispheres being not more than 4 in. (10 cm.) in diameter. They are accurately turned to fit one another, and provided with a stop-cock to exclude the air when they are taken from the air-pump (Fig. 33), and with handles. Two persons must exert all their force if they would separate them.

A Shrivelled Apple and a half-filled bladder, if placed under the bell-jar receiver of an air-pump, expand when the pressure

of the atmosphere is removed. The air inside the skin of the apple or the bladder expands. The skin is filled out and the apple and bladder appear round and firm, only to return to their shrunken condition when the air is admitted again. If the hand be placed on some hollow vessel, such as that shown in Fig. 32, the removal of the atmospheric pressure from the palm of the hand causes it to swell. The pressure on the rest of the body causes pressure to be communicated to the fluids in the part where pressure is then unbalanced.

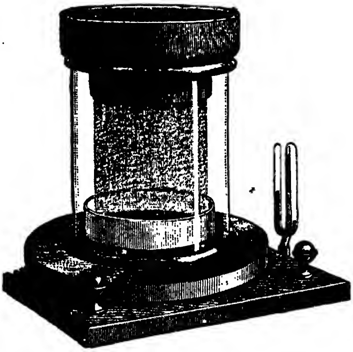


Fig. 34.—Mercury rain.

Mercury Rain.—The pressure of the air will force mercury through the pores of wood if the pressure is removed from the other side. A wooden cup is turned with its axis in the direction of the grain. If this be cemented into a glass cylinder, such as is shown in Fig. 34, and filled with mercury, when the air is exhausted from under the cup a fine rain of mercury descends in the cylinder.

With the aid of the air-pump many such experiments may be devised to show the existence of the atmospheric pressure. It seems strange that, though it is the most widespread of all pressures, Galileo should have been the first to suspect it.

CHAPTER IV

Weight of Fluid

Mass of Liquid—Mass of Gas—Density—Relative Density—Specific Volume—Fluid Pressure due to Weight—Free Surface of a Liquid is Horizontal—Horizontal Surface of Liquids—Masson's Experiment—Pressure Proportional to Depth—Equilibrium of Superposed Fluids—Thomson Sounding Machine—Hypsometry—Liquid in Communicating Tubes—Different Liquids in U-Tube—Liquids 'find their own Level'—Artesian Wells—Water Level—Spirit Level.

There are two ways in which a certain quantity of fluid may be described: there is its mass, and there is the volume which it occupies. 'A gallon of water weighs 10 lbs.,' or 'a cubic cm. of water is one gramme,' are instances of comparison between mass and volume. It is in the matter of volume that a liquid mass differs from a mass of gas. A liquid remains at the bottom of any vessel, and for the purposes of hydrostatics is of constant volume, while a gas fills the whole space open to it.

The Mass of a Liquid.—Liquids must be placed in some vessel to be weighed, and the weight of the vessel being allowed for, the mass of the liquid is found, an operation so familiar to every one as hardly to need remark.

The Mass of a Gas.—Otto von Guericke of Magdeburg (1650) seems to have been the first to observe that 'air has weight,' and therefore mass. The mass of a certain quantity of air, as of water, is found by weighing a vessel of known capacity first empty and then full of air. A thin glass vessel is cemented

on to a brass tube with a stop-cock. The end of the tube is tapped with a thread, so that it can be attached to an air-pump. A hook is screwed into the tube, so that the vessel can be suspended under the scale-pan of a hydrostatic balance (Fig. 35).

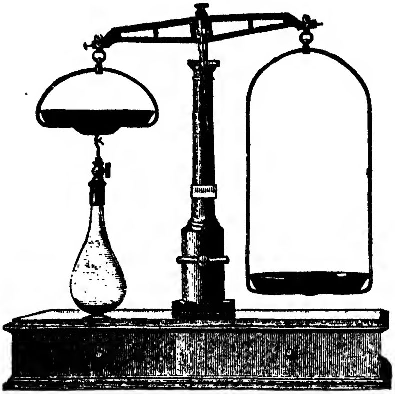


Fig. 35.—Weighing air.

The air is first exhausted from the vessel by an air-pump, the stop-cock is closed, and the weight of the empty vessel is found or counterbalanced by weights.

The tap being opened, the air rushes in and fills the vessel, which is seen at once to be heavier, as it weighs down the balance. The mass of the contained air at atmospheric pressure is found by the weights added to restore equilibrium. The volume of the vessel can be found by weighing the mercury or water which it can contain. A flask containing 250 cubic in. holds about 80 grains of air. The mass of 1 litre (cub. decimetre) of air at 0° C. and 760 mm. pressure is 1·31844 gramme (Mendeléef).

Density.—The density of a substance, whether it be solid, liquid, or gas, is its mass per unit volume. A cub. in. of brass weighs 4·6 oz.; a cub. ft. of water weighs 1000 oz. (62·4 lb.); a cub. decimetre (or litre) of air weighs 1·3 gramme. So the density of brass is 4·6 oz. per cub. in.; of water, 62·4 lb. per cub. ft.; of air, 1·3 gr. per litre.

Density or absolute density is an estimation of mass per unit volume. Owing to the various units of mass and volume, measurements of the same density have many numerical values, and this would lead to confusion; it is consequently usual to consider the density of a substance in its relation to the density of some well-known standard substance.

Relative Density is the ratio of the density of a substance

to the density of some standard substance. The density of water is the standard of density for solids and liquids, and the density of hydrogen the standard for gases. Water is easily obtained and is of uniform quality; hydrogen can easily be obtained pure and is very light.

If a cub. ft. of water weighs 1000 oz. and a cub. ft. of brass weighs 8000 oz.: the relative density of brass is 8. Here a cub. ft. is taken as the unit of volume; but as any volume may be taken for the unit, relative density is usually defined as follows: *The Relative Density of a Substance* is the ratio of the mass of a body composed of it to a mass of an equal volume of the standard substance. (Water at 4° C. for solids and liquids. Hydrogen at 0° C. and 760 mm. pressure for gases.)

It is sometimes convenient to describe the density of a fluid in terms of the volume occupied by a unit mass of it; this is usually compared with the volume occupied by unit mass of the standard substance.

The Specific Volume of a Substance is the ratio of the volume occupied by unit mass of it to the volume occupied by unit mass of the standard substance.

There is an unfortunate divergence between the English and scientific methods of estimating mass and density. In the English method masses are estimated by weighing against brass weights in air, and compared for density with water at 60° F. or 62° F. In the scientific method, masses are weighed in vacuo and compared with water at 4° C. (39° F.). The effect of these differences is referred to in connection with the Comparative Scales on p. 106.

As masses are estimated by weighing, it is usual to compare the weights of equal volumes of a substance and water; this ratio is called specific gravity. Since the weight of a body is proportional to its mass, specific gravity does not differ from relative density. Specific gravity is discussed in Chap. V.; what has been said now of mass and density is necessary for the consideration of pressure due to the Weight of Fluid.

Fluid Pressure due to Weight.—The mass of fluid is that

on which the earth exerts that force which we call its weight; it is of the weight of fluids as causing fluid pressure that this chapter treats.

Within a fluid, above any small area, there is fluid whose weight exerts a force across that area on the fluid below it. It is one of the properties of fluids that force exerted in a fluid is of the same intensity in all directions. Thus the weight of fluid must cause fluid pressure in it.

The Free Surface of a Liquid is Horizontal.—A surface of water if unruffled by wind is perfectly flat and 'level.' The sea or any large expanse of water is seen to have a curved surface which is a part of the spheroidal surface of the earth. Any small portion of a liquid surface is equally part of a spheroidal surface, but being small is nearly a plane to which a vertical line is perpendicular; this is what is called 'horizontal.' Every part of a liquid surface is practically at the same distance from the earth's centre, and this is what is called a 'level' surface. Such considerations afford a sufficient and satisfactory proof that the free surface of a liquid is horizontal, but a simple explanation can be given of the behaviour of a small surface when disturbed.

Horizontal Surface of Liquids.—Suppose a perfect liquid surface at rest, if possible with B higher than C (Fig. 36). If B and C be near one another, BC may be considered as a small prism of liquid on an inclined plane. There can be no shearing stress in a perfect liquid, so that the liquid can exert on BC no force along BC. To the weight of this prism, which is a vertical force, the fluid pressure can only oppose a force perpendicular to BC, and if BC be not horizontal there must be a component of the weight in the direction BC which is not opposed, and the prism must slide down. Therefore no perfect liquid can rest with its surface otherwise than horizontal. A real liquid opposes no permanent shearing stress, and so rests horizontally.

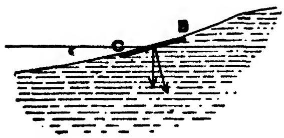


Fig. 36.—Surface of liquid horizontal.

Masson's Experiment or **Pascal's Vases.**—Glass tubes or

'vases' A, B, C, D, of various shapes, are cemented into brass collars which screw into an opening at P (Fig. 37). When this opening is closed the vase can be filled with water. A brass plate fits water-tight against the opening, and is kept against it by one arm of a balance, so that a known force can be exerted by the plate against the water when the vase is filled.

Fill one of the vessels, A, with water, putting weights into the scale-pan and marking by the index T the height of the water when it begins to flow out below. If B, C, D are placed on the opening and carefully filled, the water reaches the same height by

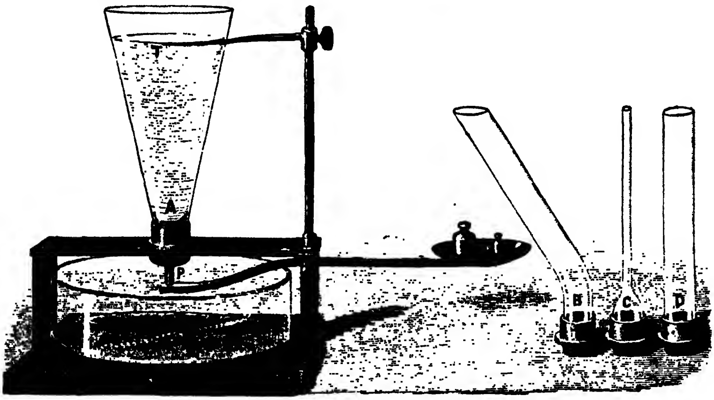


Fig. 37.—Masson's apparatus.

T when it begins to flow out below. It is not possible to be very accurate in marking the height, as the flow of the water is uncertain. The experiment assumes that this takes place when the downward thrust of the water is equal to the upward thrust of the brass plate due to the weights in the balance, and in the main this is so. It proves that the force exerted at P does not depend on the amount of water in the vases but on its height.

The pressure at a point in a liquid depends only on the depth of the point below the free surface.

The opening at P is of the same area for all the vases, and as the fluid pressure exerts equal force in all cases on this area

the intensity of the fluid pressure at the bottom of the vessel is the same in all cases.

Pressure Proportional to Depth.—*The pressure at a point in a heavy homogeneous fluid, not exposed to external pressure, is proportional to the depth of the point below the surface.*

Consider a tube of inside sectional area 1 sq. in. (or sq. cm.) placed vertically in water. The weight of water in the tube is a force acting vertically downwards. The tube exerts no vertical force on this water, as the pressure on the sides is everywhere horizontal.

Consequently the whole weight of the water is exerted on the unit area of water at the end of the tube, causing a fluid pressure measured by the weight of that water on the sq. in. (or sq. cm.).

The pressure at a point is caused by the weight of the column of water above it, and this weight varies as the depth of the point below the surface.

There need not be a tube at all, for, considering the vertical column of water separately, the water round it can exert no vertical force on the column, as all the pressure on it must be horizontal.

And there need not be a fluid column extending vertically from the area considered to the surface; for example, there is not in the case of vase B (Fig. 37). The thrust on the area P would not be different if the vase were placed in fluid whose surface is at the same height A as the water inside B. (Fig. 38); nor different if the vase were removed. Then the column of water as shown dotted would be standing vertically above the area P. The pressure at a point in a fluid depends only on the depth below the surface.

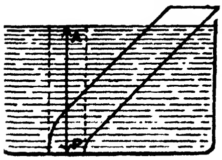


Fig. 38.—Slanting vase.

As an example the lock-gates at the entrance of a ship canal may have to hold back the whole ocean when it is high water and the lock is empty; or they may have to hold back the lock full of water only when it is low water and the lock is full.

The level of the water being the same, the force exerted by the lock-gate is the same in both cases, and depends only on the depth of the water, not on the amount of water. This illustration is often given, but it is a bad one, because both cases could not occur with the same gates. They are fitted to open in one direction only, and they do not stand pressure on the side from which they open.

Since the pressure in a fluid at rest varies as the depth, the intensity of the pressure is the same at all points in the same horizontal plane.

Equilibrium of Superposed Fluids.—Suppose that two fluids which do not mix are placed in a vessel, the denser one occupies the lower part of the vessel, and their common surface is horizontal (Fig. 39). Some oil is placed in a tall vessel and then some water is poured down a rubber tube to the bottom; the oil rises on the surface of the water and the common surface of the oil and water is horizontal.

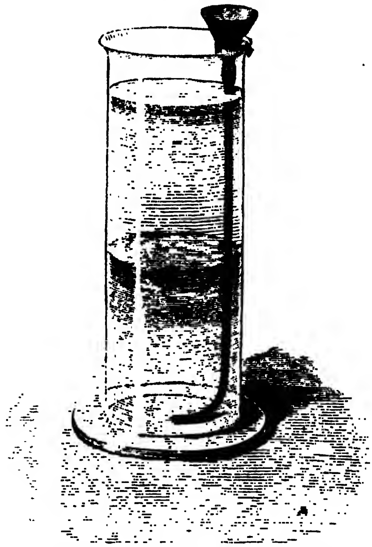


Fig. 39.—Common surface horizontal.

An open tall jar like that in the figure above is empty, that is, it contains only air; carbonic acid is a gas heavier than air, and if it is poured down to the bottom of the jar through the tube, then it will lie like the heavier liquid at the bottom, and the common surface is horizontal. In a tidal river, the salt water is often seen flowing up underneath, while the fresh water goes down on the top. In a coal mine, after an explosion, the carbonic acid occupies the lower part of the workings and galleries, and men try to avoid the gas by keeping above it.

Thomson Sounding Machine.—The atmospheric pressure supports a column of water 33 ft. high, consequently at a depth of 33 ft. (roughly, 5 fathoms) the pressure due to the weight of water is one atmosphere, the total pressure two atmospheres. If a tube closed at one end be lowered to a depth of 5 fathoms, the air in it is compressed into half its original volume, and water goes half-way up the tube; at a depth of 10 fathoms, $\frac{2}{3}$, and of 15 fathoms, $\frac{3}{4}$ of the length.

In Lord Kelvin's Sounding Machine, a tube about 24 in. long, and not more than $\frac{1}{10}$ in internal diameter, shown broken in half at A, is closed at B (Fig. 40), and lined inside with a brown chemical. The sea-water turns this brown coating white so far as it has entered the tube. The glass tube is enclosed, open end downwards, in a brass case and attached to a line, a sinker being made fast at the end. The line is a piano wire, 300 fathoms long, which offers little resistance to the sinker and is strong enough to haul it in again. In ordinary sounding with a lead, the ship must be slowed down to about 5 knots, but the Thomson sounder is run out and hauled in when the vessel is going full speed.[1] The tube is then placed on a gauge, shown in the figure below AB, and the depth indicated by the white marking is read off in fathoms, as explained above. The scale reads 100 fathoms at $\frac{1}{20}$ of its length.

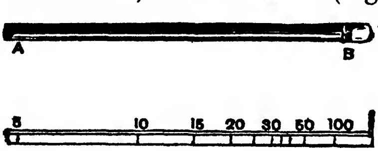


Fig. 40.—Thomson sounding machine and scale.

Hypsometry (*ὕψος*, *hypsos*, high), the measurement of heights. The earliest experiments on atmospheric pressure showed that the cause of the pressure of the air must be the same as the cause of the pressure of water, viz. the weight of the fluid itself. For this reason the height ascended can be measured by the change in the atmospheric pressure just as a sounding is

[1] This is true of moderate speeds. In experiments made in 1897 by Lord Kelvin on board R.M.S. *Campania*, going $21\frac{3}{4}$ knots, the sinker got down $28\frac{3}{4}$ fathoms with 150 fathoms of line out. He estimated that if the whole 300 had run out, 50 fathoms would have been reached.

taken by the pressure of the water. It is not, however, so simple a matter to construct a hypsometric scale; the intensity of pressure in air is not connected with the depth by a simple ratio. Pressure in a gas causes compression and increase of density, and since there can be no gas where there is no pressure, there is no free surface from which to measure depths.

For places near the earth's surface the height of the barometer diminishes by $\frac{1}{10}$ in. for every 90 ft. of ascent; corrections are necessary for temperature and humidity. Mr. Glazebrook gives the following general rule for finding the difference in level between two stations. *Multiply the difference between the logs. of the two barometer readings by two millions. The result will be the difference in centimetres.*

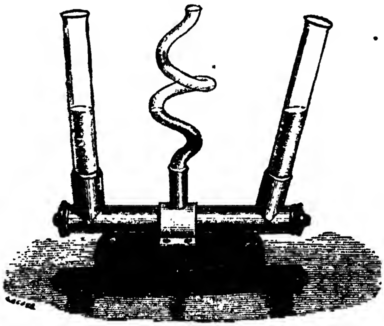


Fig. 41.—Communicating tubes.

Liquid in Communicating Tubes. — Tubes of various shapes open into a horizontal tube and so communicate with one another (Fig. 41). If a coloured liquid be poured into them it can be seen standing at the same height in all the tubes. In this way it is said that '*water finds its own level*,' and the cause is the same as that of the horizontal free surface of a liquid, viz. that all points of the surface are practically at the same distance from the earth's centre.

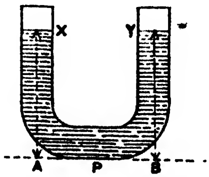


Fig. 42.
Equilibrium of liquid in U-tube.

Suppose a U-tube (Fig. 42) filled with a homogeneous liquid, and consider the force or thrust across a vertical section of the tube at its lowest point P. There is a fluid pressure measured by the weight of a column of unit area, and height YB, causing a force or thrust towards the left, and there is a force towards the right, corresponding to the

height XA. Since the liquid is at rest, these forces are equal, and therefore the columns XA and YB must be of equal height.

Therefore a homogeneous liquid rises to the same height in communicating tubes.

It should be noticed that the pressure at the point P to right or left depends on the height of the columns XA and YB, not on the amount of liquid in the tubes, so that the communicating tubes may be of very different cross-sections.

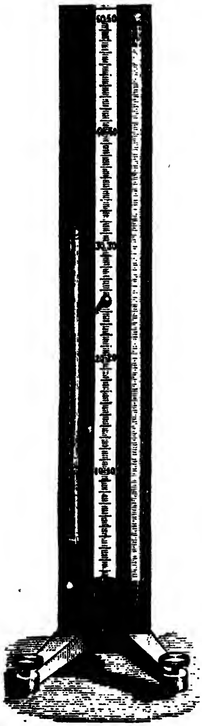


Fig. 43.
Different liquids in U-tube.

Different Liquids in U-Tube.—If there are two different liquids, such as mercury and water or oil and water, in the two branches of a U-tube, the heavier liquid does not rise so high as the lighter one.

In Fig. 43 the mercury column YB is 3·5 cm., and the water column XA is 47·4 cm. above the common surface at A in the right-hand tube.

Consider so much of the mercury as is below this horizontal plane AB on both sides; this would be in equilibrium if the part above it were removed. Hence there must be an equal pressure on it in both branches at the points A and B in that plane.

A column above A of unit sectional area of the liquid in that branch must weigh the same as a similar column of the other liquid above B, and therefore their masses must be equal.

But the column of water above the common surface stands $13\frac{1}{2}$ times as high as the column of mercury above the same; the volume of the column of water is $13\frac{1}{2}$ times the volume of the column of mercury. Therefore the *relative density* of mercury is $13\frac{1}{2}$.* The relative density of liquids which do not mix with

water can be found by this method, or of any liquids if mercury be placed in the bend.

Liquids 'find their own Level.'—From the Lecture Room experiment of Fig. 41, and from general considerations, it has been observed that since the surfaces of liquids in communicating tubes are in the same horizontal plane, liquids are said to 'find their own level.' The water-supply of towns depends on this principle: the Liverpool supply from Lake Vyrnwy passes underneath the Weaver and the Mersey and rises to the city itself. The reservoirs of towns are, if possible, placed on a height, and the water is then delivered everywhere by its own weight.

It not unfrequently happens that air in the pipe prevents liquids from finding their own level. Suppose that a reservoir X whose surface is at A (Fig. 44) is expected to discharge into

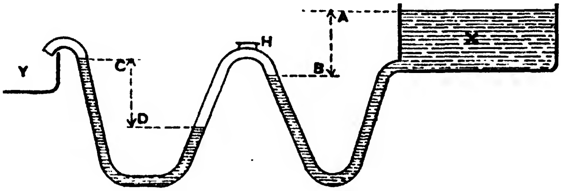


Fig. 44.—Air-block in water-main.

another reservoir at Y at a lower level, after passing a hill at H. If by any means air gets into the pipe at H, the pipes having water in them, this air communicates pressure, and so long as the difference in height between the surfaces A and B is equal to the difference in height between the surfaces C and D, it is evident that the water will not flow, though A be higher than C.

To avoid this an air-valve is fitted. There is an aperture at H by which air can escape; a light ball which floats on the water as it rises closes this aperture when the surface B has risen above the bend.

This behaviour of air in a pipe should be noticed; as a matter of interest it is a good example of the transmissibility of fluid pressure, but as a matter of experience it often causes trouble in pipes apparently well laid.

Artesian Wells.—If a porous stratum P lie between two impervious strata C of a saucer shape, the porous stratum will become filled with water from the ends where it crops out (Fig. 45). If a boring be made at the bottom of the valley the water

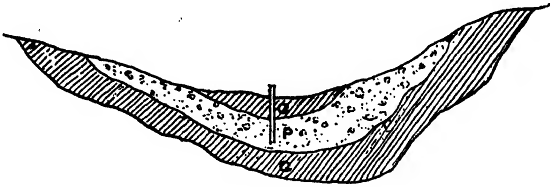


Fig. 45.—Artesian well.

may spring to a considerable height because of the porous stratum being filled with water above that height. Artesian wells are sometimes bored to a great depth with the object of securing a flow of water. William Whiteley's well is 600 ft. deep.

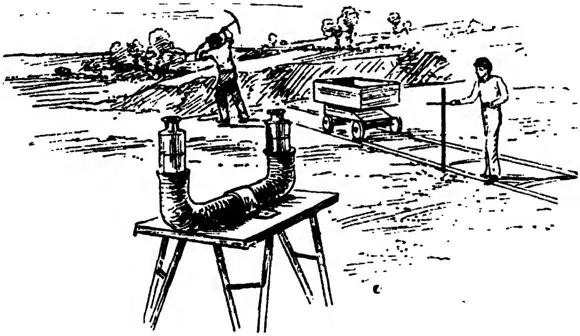


Fig. 46.—Water level.

The Water Level is a simple apparatus for finding 'levels,' *i.e.* points which are in the same horizontal plane. In one of the public schools a field was levelled for cricket by the boys themselves; one of them made his own water level and set out the work with it. Two small bottles whose bottoms have been removed are let into the ends of a lead pipe turned up as shown

in Fig. 46, and are cemented in with red lead. The whole is filled with coloured liquid; the eye can then detect a point on a distant staff which is in line with the two liquid surfaces, and is therefore at the same level as they are.

The Spirit Level is the instrument usually employed for 'taking levels.' A short glass tube whose axis is an arc of a large circle is closed at both ends and filled with spirit, all but a very small '*bubble*' of spirit vapour. If the arc be in a vertical plane the bubble rests in it at a place where the tangent to the arc is horizontal.

It is usual to fix the tube in a holder, as is shown in Fig.

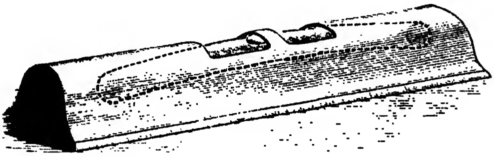


Fig. 47.—Spirit level.

47; the bottom of the instrument is truly horizontal when the bubble is in the middle.

For surveying, the spirit level is used in connection with a telescope and mounted on a tripod stand. The telescope has cross-wires at the common focus of eye-piece and object glass; points in line with the axis of the telescope can be accurately observed. The spirit level is fastened to the telescope, so that the axis may be horizontal when the bubble is at a certain mark. The axis of the telescope is parallel to a tangent plane to the tube at that mark. The surveyor brings the bubble to the mark, then distant points whose images, formed by the object glass, coincide with the horizontal cross-wires, are at the same level.

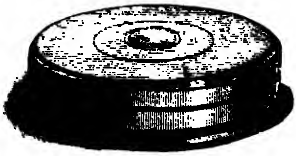


Fig. 48.—Spirit level, circular form.

Fig. 48 represents another form of spirit level which is often used in laboratories for placing instruments horizontally by the set screws. The spirit is in a small circular vessel with a glass

top, the under side of which is slightly concave. A 'bubble' is left and a circle etched on the glass of the same size as the bubble.

The top is part of a sphere on which the bubble must always mark a horizontal circle, so that if the base be parallel to the circle on the glass, it must be horizontal when the bubble fits the circle.

CHAPTER V

PRINCIPLE OF ARCHIMEDES

Resultant Pressure—Resultant Pressure on an Immersed Body—Principle of Archimedes—Cartesian Divers—Floating Bodies—Equilibrium of Floating Bodies—Stability—Specific Gravity of Solids—The Hydrostatic Balance—Nicholson's Hydrometer—Joly's Balance—Specific Gravity Bottle—Specific Gravity of Liquids—Wilson's Specific Gravity Balls—Specific Gravity of Gases—Archimedes' Principle applied to Gases—Mass and Weight—Balloons—Phial of Four Liquids.

Resultant Pressure is the force which a fluid exerts on a surface exposed to it. If the surface is a plane the resultant pressure is a force perpendicular to the plane and equal to the sum of all the forces which the fluid exerts on small areas of it.

The force which the fluid exerts on a horizontal area of one square inch (or sq. cm.) is the weight of the column of the fluid one square inch (or sq. cm.) in section which is above the area. Consequently the resultant pressure on a horizontal plane in water acts through the c.g. of the plane and is a vertical force equal to the weight of a column or prism of water reaching from the immersed plane vertically to the surface.

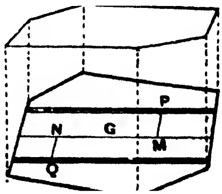


Fig. 49.
Resultant pressure on plane.

If the plane be now turned about a horizontal line MN through the centre of gravity G (Fig. 49) the force on a small horizontal strip (Q) that is lowered is increased, and the force on a small horizontal strip P that is raised is equally decreased.

Hence the resultant pressure or total force exerted by the fluid on the plane remains of the same magnitude.

The resultant pressure on a plane immersed in water is equal to the weight of a column of water of sectional area equal to the plane, and height equal to the depth of the c.g. of the plane.

This force acts perpendicularly to the plane, but only through the c.g. if the plane is horizontal. If the plane is not horizontal the force acts through another point called the *Centre of Pressure.*

Resultant Pressure on an Immersed Body.—If two equal pieces of lead be suspended by a string over an easily running pulley, they rest in any position (Fig. 50). If now a tumbler of water be brought underneath one of them, and it be lowered into the water, it does not rest there, but rises to the surface, as though it had become lighter by being in the water. This experiment shows that the resultant pressure of water on the lead immersed in it is a vertical force acting upwards, which counterbalances part of its weight; it 'loses part of its weight.'

Fig. 50.
Resultant pressure on immersed body.

The Principle of Archimedes is so called because it was first discovered by Archimedes 287 B.C.

A body wholly immersed in water loses a part of its weight equal to the weight of the water displaced.

The truth of the principle of Archimedes may be shown by the following experiment. A hollow cylinder B is suspended from the short arm of a Hydrostatic Balance (Fig. 51), and underneath it is suspended a solid cylinder A, which fits exactly into the hollow cylinder, as shown enlarged on the

right. The whole is counterbalanced by sufficient weights in the other scale-pan.

A beaker of water is brought underneath the cylinders and raised on blocks, so that A is entirely immersed; the water exerts a vertical upward force on A, which makes it appear to 'lose weight.' The hollow cylinder is now filled with water by

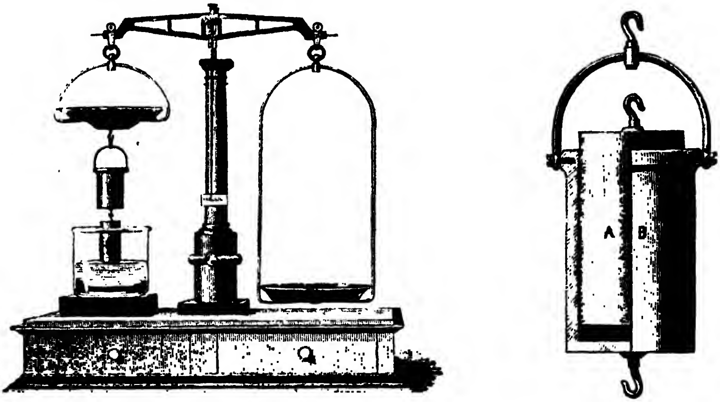


Fig. 51.—Principle of Archimedes.

means of a syringe, and when it is full equilibrium is once more restored.

This shows that the upward force or loss of weight is equal to the weight of a mass of water equal in volume to the cylinder A which is immersed.

The general truth of the principle of Archimedes is seen by the following consideration. Suppose a solid body, of any material or shape, wholly immersed in water being tied to the bottom if lighter than water, as A, or suspended by a string if heavier, as B (Fig. 52). The forces exerted on it by the fluid pressure are the same whatever its substance may be. Now suppose that it be made of water, *i.e.* that in its place there be a portion of the water of that shape.

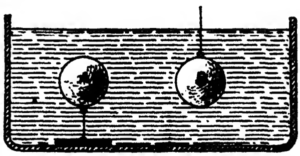


Fig. 52.—Immersed bodies.

The weight of this portion of water is a vertical force acting at its c.g. downwards. As the water is at rest, the resultant fluid pressure on the portion supposed is in equilibrium with this force. Hence the resultant pressure on the body, supposed now to be made of water, is equal to its weight, and acts vertically upward through its c.g.

The resultant fluid pressure on this body is the same whatever its substance. Therefore the force exerted by the fluid on any body immersed in it is equal to the weight of the displaced fluid, and acts vertically upward through the centre of gravity of the displaced fluid. The force exerted by the strings in either case, described above and illustrated in Fig. 52, is the difference between the weights of the immersed body and the displaced water.

The conclusions called the *Principle of Archimedes* may be summed up as follows :—

I. The force which a fluid exerts on a body immersed in it is equal to the weight of the fluid displaced.

II. It acts vertically upwards.

III. It acts through the centre of gravity of the fluid displaced, usually called the 'Centre of Buoyancy.'

Fig. 53.—Cartesian diver.

Cartesian Divers.—Descartes illustrated the principle of Archimedes with the aid of small grotesque figures, which are nearly equal but slightly less in mass than the water which they displace. They are provided with tubular tails open at the end and communicating with the hollow body (Fig. 53). One or more of these is placed in a tall jar which is nearly filled with water and covered with a sheet of rubber.

Pressure applied by the hand to the rubber causes water to enter the tail and compress the air in the body of the imp, which is then heavier than water and sinks. When the hand is

removed the air expands, the water is driven out, and the figure being lighter than the water displaced rises to the surface. These are called *Cartesian Divers*, after their inventor.

Floating Bodies.—If a vessel be perfectly full of water and a light body be floated in it, some water overflows. For this experiment it is best to have a beaker with a tube inserted in the side (Fig. 54), as it is then perfectly full when the overflow from the tube ceases. When the body is floated in it the water flowing from the tube is received in another beaker and weighed. The displaced water is found to be equal in weight to the floating body.

Fig. 54.—Floating body.

Equilibrium of Floating Bodies.—If a solid be floating in water or any liquid it is displacing some liquid which would be there if the solid was not. The forces acting on the solid are: its weight acting through its c.g. and the resultant pressure of the liquid—a force equal to the weight of the displaced liquid and acting through the c.g. of the displaced liquid, called the *Centre of Buoyancy.* Both of these forces are vertical, and if the solid be floating freely in equilibrium they must be equal and in one straight line.

A floating body is in equilibrium when the weight of the body is equal to the weight of the liquid displaced, and the centre of buoyancy is in the same vertical line with the c.g. of the body.

These are the conditions if the body is at rest. If it be slightly displaced and when released returns to its former position, it is said to be in *stable* equilibrium; if, being released, it moves further from its original position, it is said to be in *unstable* equilibrium.

Stability.—Stable equilibrium of floating bodies is of great importance in connection with ships. Consider the case of the ship shown in section in Fig. 55. The c.g. of the ship is at G; the centre of buoyancy is at B. So long as the ship floats

upright these two are in the same vertical line, the middle line. When the ship is inclined a little (Fig. 56) the centre of buoyancy is shifted to B. The weight of the ship W acts through G, and the resultant pressure or buoyancy acts vertically upwards through B in a vertical line, which cuts the middle line in M. This point is called the *Metacentre*. So long as the metacentre is above G the weight W and the buoyancy W form a couple $W \times GZ$, tending to right the vessel. If the metacentre were below G the opposite would be the case, and the vessel would roll over. The stability of the vessel depends on the position of the metacentre and the magnitude of this couple. The distribution of the weights on board a ship,—guns,

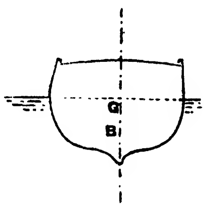


Fig. 55.—Ship on even keel.

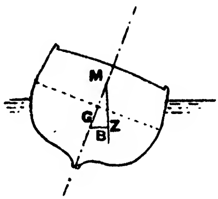


Fig. 56.—Ship inclined.

armour, engines and boilers, are settled by the special requirements of the case. It is the object of the naval architect so to design the hull that the centre of buoyancy may be at some distance from the middle line when the ship is displaced. As the metacentre may be above G when a vessel is 'light,' *i.e.* without cargo, ballast is put in her hold to bring the c.g. down lower.

If there is any doubt about the stability of a vessel she is 'inclined for stability' before she is sent to sea by placing weights at known distances from the middle line, so that the inclining couple is known; the moment of the couple necessary to incline her through certain angles is ascertained, and from this the metacentric height is determined.

Specific Gravity of a Substance is the ratio of the weight of any volume of it to the weight of the *same* volume of water at

60° F. In the C.G.S. system water at 4° C. is taken as the standard substance. (Continued from p. 185.)

I. The specific gravity of a solid body may be ascertained *by measurement.*

The weight of any given volume of water is known. If the volume of the body and its weight are known, its specific gravity can be calculated.

An armour plate is 6 feet × 5 feet × 9 inches, and weighs 4·82 tons; what is its specific gravity?

Cubic content of plate $= 6 \times 5 \times \frac{3}{4} = 22\frac{1}{2}$ cub. ft.
Cubic ft. of water = 1000 oz.
Weight of equal volume of water = 22500 oz.
" " $= 1406\frac{1}{4}$ lbs.
Weight of plate = 4·82 tons = 10796·8 lbs.
Specific gravity of plate $= \frac{10796}{1406} = 7{\cdot}68$ nearly.

The principle of Archimedes simplifies the determination of specific gravity by making it easier to ascertain the volume of an irregular body. A body wholly immersed in water loses a part of its weight equal to the weight of the water displaced, so the weight of water equal in volume to any body is easily found. It was in reality this which was the great discovery of Archimedes. He noticed the overflow of a brimming bath as he got into it, and he saw that he had thus a ready means of ascertaining the volume of a body, of however complicated a shape.

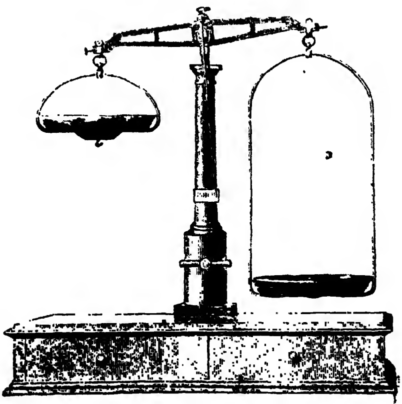


Fig. 57.—Hydrostatic balance.

II. **The Hydrostatic Balance.**—One scale-pan of a balance being removed, another of the same weight but with shorter chains is substituted for it (Fig. 57). This has a hook under the pan from which a small body may be suspended when

its specific gravity is to be found. The balance thus arranged is called a *Hydrostatic Balance.* If no short scale-pan is provided, a bridge may be put across the ordinary scale-pan, which usually has a hook under its point of support to serve for suspension of bodies. The weight of the body is first determined as it hangs in air. A beaker full of water is then brought up underneath, as in Fig. 51, until the body is wholly immersed. The body appears to lose weight. Some weights are removed, and the weight of the body in water is determined. This 'loss of weight' is due to the upward thrust of the water, and by the principle of Archimedes is equal to the weight of the water displaced by, and equal in volume to, the body. Thus the weight of an equal volume of water is found, and the weight of the body having also been found, the specific gravity of the body is the ratio $\frac{\text{weight of body}}{\text{weight of displaced water}}$.

Fig. 58.—Nicholson's hydrometer.

Ex. Weight of a body in air	.	390 gr.
,, ,, water	.	338 gr.
Weight of displaced water	.	52 gr.

$$\text{Sp. gr.} = \frac{390}{52} = 7 \cdot 5.$$

To find the specific gravity of a solid lighter than water by the Hydrostatic Balance a sinker is used, which may be a piece of iron or brass, with its weight in air and in water engraved on it.

III. **Nicholson's Hydrometer.**—A hollow metal cylinder is connected by a stem to a pan above and a pan below it, the whole being weighted so as to float vertically (Fig. 58); and there is a mark on the stem supporting the upper pan, which must float some way above the surface when the hydrometer is unloaded. The substance whose specific gravity is to be found is placed first in the upper, then in water in the lower pan.

To weigh the solid in air.—Place weights in the upper pan until the mark on the stem is brought down to the surface of the water. Remove the weights and place the solid in the upper pan; add weights to bring the mark to the surface again; the difference of the weights with and without the solid gives its weight in air.

To weigh the solid in water.—Place weights in the upper pan until the mark is at the surface. Remove the weights and place the solid in the lower pan, and place weights in the upper pan to bring the mark to the surface, when the difference of the weight with and without the solid gives its weight in water. The weight of the body weighed *in air* and *in water* is now known. The specific gravity is determined as before.

Ex. Weights required to bring Nicholson's Hydrometer to float at given mark :—

Wt. required without solid	453 gr.	Wt. required without solid	453 gr.
,, with solid in air	63 gr.	,, with solid in water	115 gr.
Wt. of solid in air	390 gr.	Wt. of solid in water	338 gr.
,, water	338 gr.	Sp. gr. $= \frac{390}{52} = 7{\cdot}5$.	
Wt. of displaced water	52 gr.		

IV. **Joly's Balance** has two scale-pans, as Nicholson's Hydrometer has, one in the air and one immersed (Fig. 59). They are supported by a spiral spring instead of by a buoyant cylinder. Determinations of specific gravity are conducted in exactly the same way as by Nicholson's Hydrometer. The example given above will serve for both. There is an index on the carrying wire; this and its reflection are made to coincide at a mark in a small vertical mirror on the upright support when the body is placed first in the upper and then in the lower pan. It is easier to do this accurately than to bring the mark on the stem of Nicholson's balance to the surface of the water, and the instrument is preferable on that account.

The accurate reading of Nicholson's Hydrometer depends on the buoyancy of small portions of the stem, and the capillary adhesion of the water to the stem interferes with its free motion.

V. **The Specific Gravity Bottle** is specially suitable for finding the specific gravity of powders and small bodies like gravel or shot. A wide-mouthed bottle has a well-fitting ground-glass stopper through which a fine hole is bored (Fig. 60). When the bottle is filled with water and the stopper is slowly pressed in, the water oozes through the stopper. This avoids air remaining in the bottle, and makes accurate filling easier. The cubic content of the bottle or the weight of contained water at a certain temperature is usually etched on it.

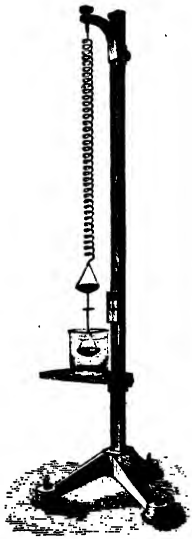


Fig. 59.
Joly's specific gravity balance.

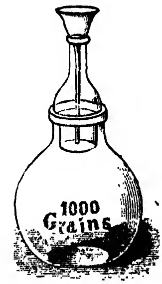


Fig. 60.
Specific gravity bottle.

If a 1000 gr. bottle be filled with water and 500 gr. of shot be put into it, the shot and water together would weigh 1500 gr. if no water escaped from the bottle. But water equal in volume to the shot will escape, and therefore the bottle after the shot is put in it weighs less than 1500 gr. by the weight of the water displaced.

The ratio of the weight of the shot to the weight of water displaced by it is the specific gravity of the shot.

Ex. Some shingle weighing 565 gr. is put in a 1000 gr. s.g. bottle, and the whole then weighs 1370 gr. exclusive of the counterpoise.

Weight of substance and water, if none escape . . .	1565 gr.
,, ,, remaining after escape .	1370 gr.
Weight of displaced water	195 gr.

$$\text{Sp. gr.} = \frac{565}{195} = 2{\cdot}9.$$

The Specific Gravity of Liquids.—The principle of Archimedes is also applied to finding the specific gravity of liquids,

and the same order may be conveniently followed in describing the various methods.

I. By Measurement.—If a liquid does not mix with water, it can be placed in a U-tube with water, or if it does, mercury may be placed in the bend. The ratio of the height of the water above the level of the common surface to that of the liquid is the specific gravity of the liquid (see p. 192).

II. The Hydrostatic Balance.—A ball of platinum or of some material which sinks in the liquid and which the liquid does not attack chemically, is suspended from the short arm of a Hydrostatic Balance.

The ball is weighed in air, in water, and in the liquid. The weight of the liquid and of water displaced is thus found, and the ratio of these two weights is the specific gravity of the liquid.

Ex. A platinum ball weighs—

219·2 gr. in air,
209·0 gr. in water,
210·6 gr. in oil.

Weight of oil displaced = 8·6 gr.; of water displaced = 10·2 gr.

Specific gravity of oil $= \frac{86}{102} = \cdot 84$.

III. *The Hydrometers.*—(*a*) Nicholson's Hydrometer is described as a hydrometer 'of constant volume'; since it is always brought down to the same mark, the volume immersed is always the same. Such a hydrometer may be used to find the specific gravity of a liquid. The weight of hydrometer and weights necessary to bring it down to the mark in water gives the weight of displaced water, which is often marked on it. The weight of hydrometer as weighted to bring it down to the mark in the liquid gives the weight of displaced liquid. The ratio of this weight to the weight of displaced water is the specific gravity of the liquid.

(*b*) The Common Hydrometer is a hydrometer 'of variable volume' (Fig. 61), because the volume immersed varies, and the specific gravity of a liquid is found by the volume of the

hydrometer immersed. It is usually made with a glass stem and bulb, which is weighted at the bottom to make it float upright.

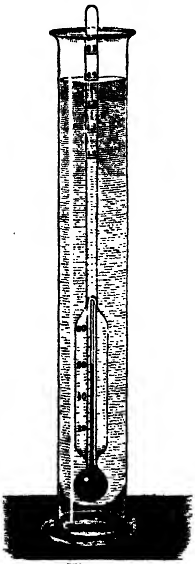


Fig. 61.
Common hydrometer.

A unit mark is etched on the stem at the place to which it sinks in distilled water at 4° C. (or 60° F., see p. 185). The weight of the liquid displaced by the hydrometer is constant and equal to the weight of the hydrometer. In a liquid heavier than water a less volume of liquid is displaced and the hydrometer floats higher. In a liquid lighter than water more liquid is displaced and the hydrometer sinks lower. Marks are etched on the stem giving the specific gravity of liquids in which the hydrometer sinks to those marks. The s.g. of the liquid in Fig. 61 is 0·9 at 60° F. These glass hydrometers are now provided with thermometers in the stem, an important addition, since the specific gravity of a liquid varies considerably with the temperature. The differences in the volumes of liquid displaced are the segments of the stem between these marks, so that the sensitiveness of a hydrometer depends on the thinness of the stem. To detect small differences in specific gravity the stem must be thin, while to measure widely different specific gravities the stem must be thick.

Hydrometers are graduated for special purposes. Brewers and Excisemen, Electricians, Chemists and Engineers have special requirements, and though ordinary graduations reading the specific gravity only might be used, still it is more convenient to have the strength of a spirit or the quality of milk indicated without calculation. Alcoholometers, Lactometers, and Brine-testers are hydrometers of variable volume graduated for special purposes.

IV. THE SPECIFIC GRAVITY BOTTLE.—It is convenient to

have a wide-mouthed specific gravity bottle for solids (Fig. 60), and a narrower mouthed bottle for liquids (Fig. 62). The weight of the distilled water at 4° C. (or at 60° F., as above) which the bottle contains is etched on the bottle. When a specific gravity bottle has been filled and wiped, if it be then held in the hand the liquid in it is warmed, and expanding oozes through the stopper, showing the necessity of attention to temperature. The weight of the empty bottle is first ascertained and left in the scale as a counterpoise. It is then only necessary to fill the bottle with the liquid whose specific gravity is required and to weigh it with the counterpoise in the other scale-pan, the ratio of the weights is the specific gravity.

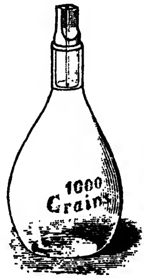


Fig. 62. — Specific gravity bottle, wide mouth.

Suppose, for example, a bottle whose water value is 1000 gr. holds 715 gr. when filled with ether, the specific gravity of the ether is ·715.

Specific Gravity Balls.—Hollow balls of glass, if made of weight exactly equal to the weight of liquid they displace, float in any position in a liquid. Sets of these are prepared for any specific purpose in very closely graduated differences between certain limits. The density of a liquid may then be ascertained to the closest approximation by choosing the ball which will just float or rest in any place in the liquid. They are usually called *Wilson's specific gravity balls, bulbs, or beads.*

The Specific Gravity of Gases may be ascertained by means of the apparatus used to show that 'air has weight' (p. 184). The glass flask void of air is connected to a reservoir of the gas whose specific gravity is required. The weight of the flask alone is balanced by a counterpoise, and the weight of the contained gas is known by placing weights in the other scale-pan, as in the case of air.

It is a matter of general knowledge that gas expands when heated (HEAT, p. 264) and that the volume of a gas is reduced by pressure (p. 171), but at present the specific gravity of the

gas shall be considered only in standard conditions, at atmospheric pressure and at a temperature of 0° C. If the empty flask, of volume 250 cubic inches, be filled with hydrogen the gas weighs 5 grains, while if filled with oxygen it weighs about 81 gr., and if filled with water 56,447 gr. Hence, referred to water, the specific gravity of hydrogen is ·0000895 and of air ·0012932. It is convenient to adopt the lightest gas, hydrogen, as the standard for gases. Relative to hydrogen the specific gravity of hydrogen is 1, of air 14·47, and of oxygen 16.

Archimedes' Principle applied to Gases.—The resultant pressure of the atmosphere on bodies in the air is a vertical

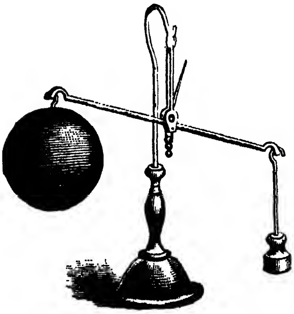


Fig. 63.—Baroscope in air.

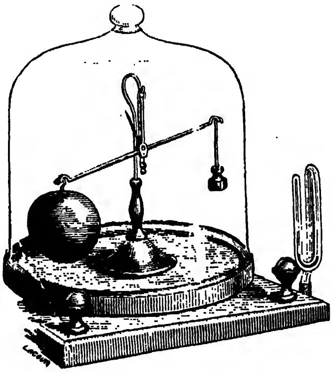


Fig. 64.—Baroscope in vacuo.

upward force equal to the weight of the displaced air. In consequence, bodies weigh more in vacuo than in air; reference is made to this difference on p. 106, and it is shown by THE BAROSCOPE. A small balance has a sphere of cork on one arm and a lead or brass counterpoise of slightly smaller mass on the other arm. When at rest in air the lead seems to be heavier than the cork (Fig. 63), but when the Baroscope is placed under the receiver of an air-pump and the air is exhausted, the cork is seen to be really heavier (Fig. 64). In air, they are both buoyed up by a force equal to the weight of the displaced air; but as the volume of the cork is much greater than that of the lead, the

force raising the cork is greater. When the receiver is exhausted the upward force is removed from both and the cork sinks.

Mass and Weight.—The comparison of *masses* by weighing can only be carried out with exactitude in vacuo. For ordinary purposes weighing in air is quite accurate enough, but in any question of exactitude the English method of weighing against brass weights in air (see pp. 105, 185) is inaccurate.

One cub. in. of distilled water, freed from air, weighed against brass weights in air (temp. 62° F., bar. 30 in.), is 252·286 grains; hence the volume of the gallon according to the Act of Parliament is 277·463 cub. in. (H. J. Chaney, for Standards Dept.).

But 252·286 grains is not the *mass* of a cub. in. of water. The weight of the air displaced by the water is ·266 gr. more than that displaced by the mass. Hence the mass of the cub. in. of water is 252·552 grains.

Balloons.—As most bodies are much denser than air, the buoyancy of the air only causes a loss of weight in them, and this being small is usually ignored. But in the case of a body of the same mass as the air displaced the resultant pressure of the air on it is a force equal and opposite to the weight, and the body floats; or if, like a balloon, it be lighter than the displaced air, it is impelled upwards. Suppose that the total mass of an empty balloon, the car, ballast, and the voyagers be 9 cwt. The density of air relative to hydrogen is $14\frac{1}{2}$, and a large balloon may displace half a ton of air. The mass of an equal volume of hydrogen is $\frac{3}{4}$ cwt., and this leaves a balance of buoyancy of $\frac{1}{4}$ cwt., which causes the balloon to rise.

A balloon is not usually quite filled with gas at first, and as it rises and the pressure of the air decreases the gas in it expands; the mass of the displaced air continues constant until the expanding gas fills the balloon; so far the lifting force continues the same. When the balloon is full, gas is allowed to escape through a valve or it might burst the silk. The lifting force then gradually diminishes till an altitude is reached where the balloon is in equilibrium. If the voyagers wish

to rise, they throw out ballast, if they wish to descend they let out gas.

On 15th September 1862, Messrs. Coxwell and Glaisher made an ascent from Wolverhampton, and Mr. Glaisher believes that before he became unconscious he read the barometer at 7 inches, corresponding to a height of 37,000 ft.; he actually recorded a reading of 9·75 inches, which showed that a height of 29,000 ft. had been attained.

Phial of Four Liquids.—With care, several liquids may be

Fig. 65.—Phial of four liquids.

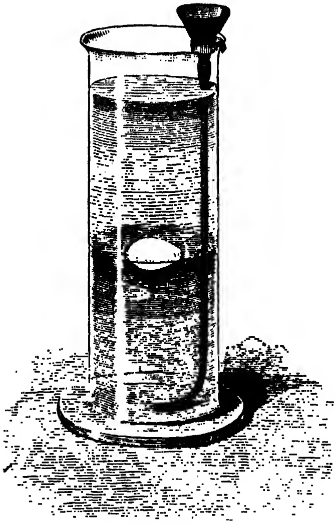


Fig. 66.—Egg on brine.

placed in a phial in the order of their density. If mercury be poured into it first and a little water be poured on the top of the mercury, some olive oil can be poured in on the top of the water, while a little spirit will float on the oil. The four liquids will be seen in the phial or a test tube in the order of their specific gravities (Fig. 65).

An interesting experiment may be made by placing an egg in some fresh water at the bottom of a tall glass. Some strong

brine is poured down a rubber tube to the bottom. The egg floats upon this, and is seen suspended in the middle of the glass (Fig. 66).

This is a fit conclusion to the subject of the Principle of Archimedes, for the egg is seen floating at a place where its weight is exactly equal to that of the displaced liquid. It is in equilibrium under the action of the equal forces; viz. its weight vertically downward, and the resultant pressure of the liquid equal to the weight of the displaced liquid vertically upward.

Specific Gravity or Relative Density

(From Lupton's Tables, by permission)

Δ is the number of grammes in 1 cub. c.m. of the solid or liquid; of gases, *printed in italics*, the number of grammes in one normal litre or $\Delta \times 1000$ (see p. 210).

Substance.	Δ	Substance.	Δ
Alcohol	0·795	*Hydrogen*	*0·0895*
Aluminium	2·7	Iron	7·76
Ammonia	*0·761*	Ivory	1·92
Bismuth	9·82	Lead	11·4
Carbon	1·8	Marble	2·7
Carbon dioxide	*1·98*	Mercury	13·6
Chlorine	*3·18*	Nickel	8·57
Copper	8·95	*Nitrogen*	*1·256*
Cork	0·24	*Oxygen*	*1·43*
Diamond	3·5	Pinewood	0·56
Glass (crown)	2·5	Platinum	21·5
Gold	19·3	Silver	10·57
Graphite	2·2	Tin	7·3
Gutta Percha	0·97	Zinc	7·2

CHAPTER VI

The Atmosphere

Mercurial Barometer—Siphon Barometer—Weather-Glass—Sympiezometer—Standard Barometer—Fortin Barometer—Marine Barometer—Vernier—Aneroid Barometer—Correction of Barometer Readings—Construction of Mercurial Barometer—Glycerine Barometer—Variations in Atmospheric Pressure.

It was necessary to refer to the pressure of the atmosphere at the very beginning of Hydrostatics, because the atmospheric pressure is so universal that it is not possible to treat of fluid pressure without referring to it. In connection with the air-pump and other experiments the magnitude of the pressure was measured. This chapter treats of the variations in the atmospheric pressure and how they are observed.

A Barometer (βάρος, *baros,* weight) is an instrument for measuring the pressure of the atmosphere.

Mercurial Barometer.—The Torricellian tube standing in its basin of mercury (Fig. 1) is the barometer in its simplest form. The pressure is measured by the height of the mercury column which the atmospheric pressure can support; so if a scale be attached to the tube to measure the distance of the top of the column above the mercury in the basin the variations in the atmospheric pressure can be observed.

But such a barometer is not convenient for use; the cistern must be connected with the tube, and the whole must be protected.

Siphon Barometer.—The first improvement, which was

suggested by Torricelli himself, is to have a tube of U-shape. The height of the column is given by the vertical distance AB between the two surfaces of mercury (Fig. 67). The form shown in the figure was suggested by Gay-Lussac, with the object of placing the two columns in one vertical line. The shorter arm B appears to be closed; there is a pin-hole at *a*, which ensures the air in B being free and at atmospheric pressure.

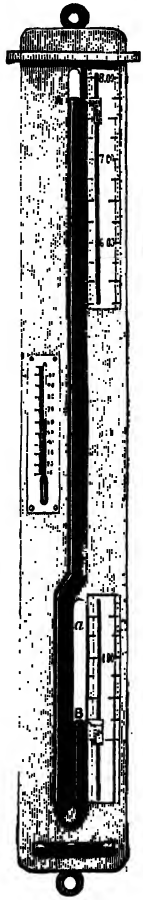


Fig. 67.
Siphon barometer.

Since the fall in one arm is exactly equal to the rise in the other, the tube being uniform, a fall of $\frac{1}{2}$ in. in the upper and closed end is accompanied by a rise of $\frac{1}{2}$ in. in the lower open end; in consequence the vertical distance AB is diminished by 1 inch. A scale of $\frac{1}{2}$ inches graduated as inches gives correct readings and may be placed by either arm.

Or the scale may be movable, and its zero be brought to the level of the mercury in the lower arm. In German instruments the tube is often made movable, and by raising or lowering the tube the surface of mercury in the lower arm is brought to the zero of the scale. In both these cases the reading is taken directly on a true scale of millimetres or inches.

Or again, as shown in the figure, there may be two scales; here the scale at A reads 775 mm., and that at B 25 mm.; the difference between the two, 750 mm., is the height of the barometer.

Weather-Glass.—A siphon-shaped tube is used in the weather-glass or *Wheel Barometer* (Fig. 68). An iron ball A floats on the mercury in the open arm. A string fastened to this ball passes over a wheel C carrying an index, and is attached to a counterpoise B. When the pressure increases, the mercury rises into the Torricellian

vacuum; the mercury, and with it the ball A, falls in the open arm. When the column falls the ball is raised and the counterpoise causes the wheel to move, and the index finger returns over the scale. This form of barometer is often met with in country inns; it is not very sensitive, a small difference in the immersion of the ball A, as the barometer rises or falls, does not exert sufficient force to move the index finger.

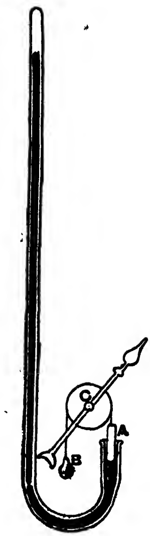


Fig. 68.
Wheel barometer.

Hence arose the custom of 'tapping the barometer' to see whether it is rising or falling. The tapping causes the weight to take up its true line of flotation if the pressure has changed.

Recording instruments are often arranged with a mass floating on the open cistern, and they are sluggish for the same reason.

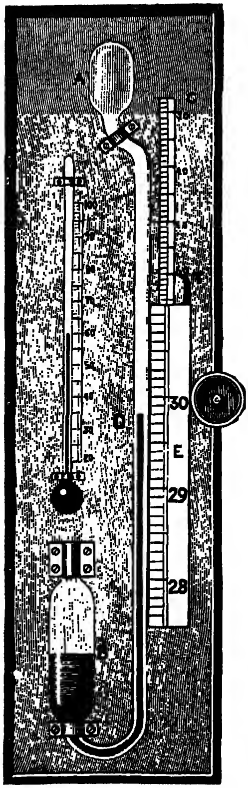


Fig. 69.—Sympiezometer.

Sympiezometer (combined pressure gauge).—A siphon tube of small bore has an air-bulb A (Fig. 69) and a large open arm B containing pink glycerine, which reaches to D in the tube. AD is an air-pressure gauge, and, so long as the temperature is constant, reads the pressure of the atmosphere on a barometer scale E. AD is also an air thermometer (HEAT, p. 266) whose scale is placed at C to be clear of E. The scale E is moved till its pointer T indicates on C the degrees of the mercurial thermometer. This instrument is very sensitive and was formerly much used at sea.

Standard Barometer.—The points are: exact coincidence of the zero of the scale with the free surface of mercury, or allowance in the graduation for the movement of the free surface; the vertical position of the scales or some mode of determining the vertical distance between the two surfaces.

The Fortin Barometer is a standard barometer in which the surface of the mercury in the cistern can be raised or lowered till it meets a fixed point; the scale is a correct scale of inches or mm. above this point. The cistern of a Fortin barometer is shown in Fig. 70. The upper part of the cistern C is a glass cylinder, and the lower part B is a leather bag. A screw with a milled head raises or lowers this bag and the mercury in it until the ivory pin P meets its own reflection in the mercury surface. The point of the ivory pin is the zero of the barometer scale.

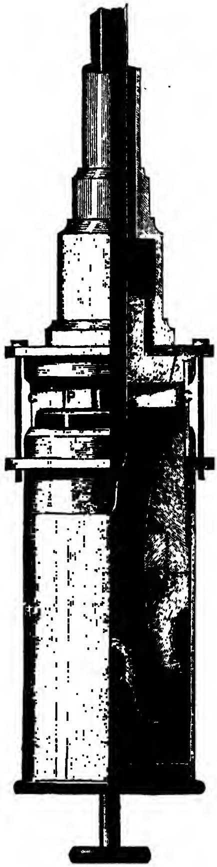


Fig. 70.—Fortin barometer.

This arrangement makes the Fortin barometer a very convenient one for observations of heights in mountain exploration, where the variations of the barometer readings are very great.

Mr. Whymper's picture (Fig. 71) shows the mode of suspension which his experience approves, and also the way in which the barometer is read; one observer adjusting the level of the cistern and the other reading the height of the column. The woodcut represents Mr. Whymper reading the height of the barometer at 14·100 in. with a temperature of 21° F. on the top of Chimborazo; the altitude given by this reading is 20,608 ft. above the sea-level. Humboldt had given the height of the mountain at 21,425 ft., and

perhaps there was a little disappointment in discovering that 'lower it would not go.'

The barometers are packed for travelling in long boxes carefully padded, and the mercury bag is screwed up till the column touches the top of the tube; they are carried with the closed end downwards.

On Mr. Whymper's travels amongst the Great Andes of the Equator the guide, Jean-Antoine Carrel, carried two of them weighing 25 lbs.

The Marine Barometer is arranged to meet the needs of

Fig. 71.—'Lower it would not go.'

seamen. In it the Torricellian tube is protected from injury by an iron tube, partly shown in Fig. 72. An iron cistern F for holding mercury is screwed on to the end of this tube. The cushion E prevents a shock to the glass tube from any blow on the iron casing. The hole D provides that the pressure on the mercury surface GG should vary with the atmospheric pressure. A diaphragm of leather prevents the escape of mercury when the barometer is inverted.

The tube is fine throughout most of its length, as shown at A, being increased to the same size as at B at the upper part, 28 to 32 in. from GG; this larger part is provided with a

scale for reading the variations in height. There is so little friction between glass and mercury that, without such a contraction, a jolt might cause the mercury to act like a battering ram and knock the end out of the glass tube. Besides this, the mercury would move up and down with every motion of the ship; an uncontrolled barometer column on shore shows this 'pumping' in a gale of wind with heavy gusts. The contraction of the tube retards the adjustment of the column to small changes of pressure, and the tube should be gently tapped if a change is suspected.

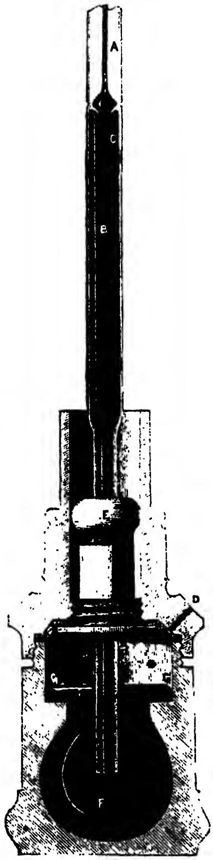


Fig. 72.—Marine barometer.

The arrangement of Negretti and Zambra's instruments is shown in Fig. 72. It is next to impossible for any air which might get into the tube at F to rise into the Torricellian vacuum. It could not enter the fine tube B, and would be caught in the air-trap C.

It is a special feature of the KEW BAROMETER, of which the Marine Barometer is one pattern, that no allowance has to be made for the rise of mercury in the cistern, as this is allowed for in the graduation. The inch readings are shorter than true inches. For example, if the area of the cistern be twenty-four times the area of the upper part of the tube, where the variation takes place, let the column rise $\frac{24}{25}$ of an inch, the surface GG falls $\frac{1}{25}$ in.; in consequence the column is one inch higher above GG than it was. The barometer will in that case read correctly if the divisions marked on the scale as inches be really $\frac{24}{25}$ of an inch.

Vernier.—By means of a vernier, so called after its inventor,

any instrument may be read to fractions of the smallest graduations into which the scale can be divided. For example, a barometer scale (Fig. 73) could not be clearly divided into smaller parts than millimetres or than twentieths of an inch. By means of a vernier, which is the part between the scales in the figure, these can be again subdivided.

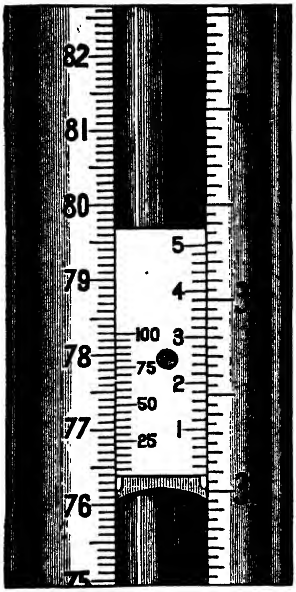


Fig. 73.—Vernier.

To read the barometer, the vernier, which is movable, is brought down so as apparently to touch the convex surface of the mercury column. In the figure, the vernier has not been brought down upon the mercury, so that this convex surface may be seen. Hence the reading of the vernier in the figure is not the reading of the barometer.

The divided portion of the vernier has one more division than the portion of the scale over which it extends; in the figure a length of the vernier equal to 19 mm. is divided into twenty parts, and a length of the vernier equal to 24 half-tenths of an inch is divided into twenty-five parts. The divisions of the vernier are numbered from zero upwards according to the fractional parts of the graduations which are to be read; in this case hundredths of a millimetre and fiftieths of the twentieth of an inch. The divisions on the right show an alternative mode of marking, 1 to 5 instead of 10 to 50.

To read the vernier, the number of the graduation next below the zero or lowest line of the vernier is first noted; here 763 mm. or 30·05 in. The zero is above these graduations by a little space; it is the estimation of the value of this space which the vernier effects. It will be noticed that this space is closed up little by little at each successive division until *a division of the*

vernier is in line or coincides with a graduation of the scale. If the first division were to coincide, the small additional space would be $\frac{5}{100}$ mm. or $\frac{2}{50}$ of the bisected tenth inch; if the second, $\frac{10}{100}$ mm. or $\frac{4}{50}$ of the twentieth of an inch. If, as in the figure, it is the 90th on the left and 36th on the right, the latter space is $\frac{90}{100}$ mm. or $\frac{36}{50}$ of the twentieth of an inch. This value is added to the value of the graduation next below the zero of the vernier. The reading of the vernier in the position shown is 763·9 mm. or 30·086 in.

Aneroid Barometer.—The difficulty of transporting mercurial barometers is very great. They are cumbrous and fragile. A form of apparatus which will register differences of pressure

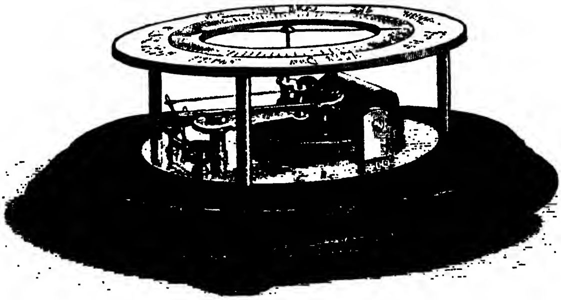


Fig. 74.—Aneroid.

accurately without the dangerous companionship of glass and mercury would be a great acquisition to mountain explorers. This was hoped for from the aneroid (*a*, not; νηρός, *neros*, liquid), the invention of Vidi, introduced to the British Association in 1848.

A flat, round box of white metal is exhausted of air. To cause its flat top and bottom to be weak to resist pressure they are corrugated in concentric rings (Fig. 74). The atmospheric pressure would force together the top and bottom of the box if this were not prevented by a pillar from the centre attached to a strong spring above it. If the atmospheric pressure increases, the spring is pulled down; if the pressure diminishes, the spring rises. These movements are very small, but are magnified by a

lever and are communicated by a rack and pinion to an index finger which traverses a dial and indicates the variations of pressure. Mr. Whymper carried five aneroids with him on the journey described in his *Great Andes of the Equator*, but he was obliged to disregard all their readings. The behaviour of these instruments under low pressures he has further described in his *How to use the Aneroid Barometer*.

Two of his aneroids read 13·05 and 12·00 respectively on the occasion referred to above, when the Fortin read 14·1 in.

For travellers who do not climb very great heights or desire great accuracy, the aneroid is a very convenient and sufficiently correct indicator of altitude.

Correction of Barometer Readings—1. PARALLAX.—The index line of the vernier should be a tangent to the curved surface of the mercury column. To avoid error through parallax the vernier (Fig. 73) is usually accompanied by a screen moving with it on the opposite side of the column. When these are kept in a line with the eye, and the vernier is brought down on the column, parallax is avoided.

2. TEMPERATURE.—All good barometers are furnished with a thermometer whose bulb is close to the barometer tube. The temperature defines the density of the mercury and the height of the column corresponding to a given pressure. Reduction tables should be made for each instrument so as to allow for the correction for expansion in all parts, the case, the scale, etc., as well as the mercury.

3. CAPILLARITY and GRAVITY.—For these, tables must also be given. But the effect of capillarity depends so much on the cleanness of the mercury that it is not easy to apply it. The correction for variation of g at different places may amount to as much as ·08 in.

4. HEIGHT ABOVE SEA-LEVEL.—The mean sea-level for the British Isles is the mean half-tide level at Liverpool. Tables are given for the correction of readings to sea-level; a simple rule is to allow 0·1 inch for each 90 ft. (See p. 191.)

5. MERCURY VAPOUR.—This is a small correction depend-

ing on temperature and usually allowed in the temperature table.

Construction of Mercurial Barometer.—The points requiring care in the construction of a mercurial barometer are:—

1. The mercury must be pure and clean.

2. The mercury must be carefully boiled in the glass tube so as to expel air and moisture.

3. The scale must be correctly divided and fixed in its true position.

Glycerine Barometer.—There are manifest advantages in the use of mercury for the barometric column in ordinary circumstances. Owing to the great density of mercury the column is short, and the pressure of mercury vapour is too small to be considered.

A barometer may, however, be constructed with any liquid, and the column being longer the changes in atmospheric pressure produce greater changes of height than in the case of the mercury column.

The pressure of water vapour being considerable (see HEAT, p. 323), a water barometer is seldom used, but glycerine does not give off vapour, and is therefore suitable for the purpose.

The column of glycerine (s.g. 1·28) corresponding to 30 inches of mercury (s.g. 13·59) is 318·5 inches, so that a glycerine column moves about $10\frac{1}{2}$ inches for every inch of the mercurial barometer. The variations of a Jordan Glycerine Barometer are given daily in *The Times*.

When it is possible to place a cistern 27 feet below a convenient place for reading the barometer, a glycerine barometer may conveniently be erected. In H.M.S. *Britannia* the cistern was in the hold and the top of the column near the other instruments.

Variations in the Atmospheric Pressure.—The earliest observations showed that the weight of the atmosphere, and so the pressure which it exerts, is continually varying. The column of mercury sometimes rises and sometimes falls, so that no constant value can be assigned to the atmospheric pressure.

Those who study the meteorological reports in *The Times* and elsewhere are acquainted with the lines of equal barometric pressure called *isobars.* These arrange themselves over the map like contour lines over country; it is with the arrangement of these that the motion of the winds is connected.

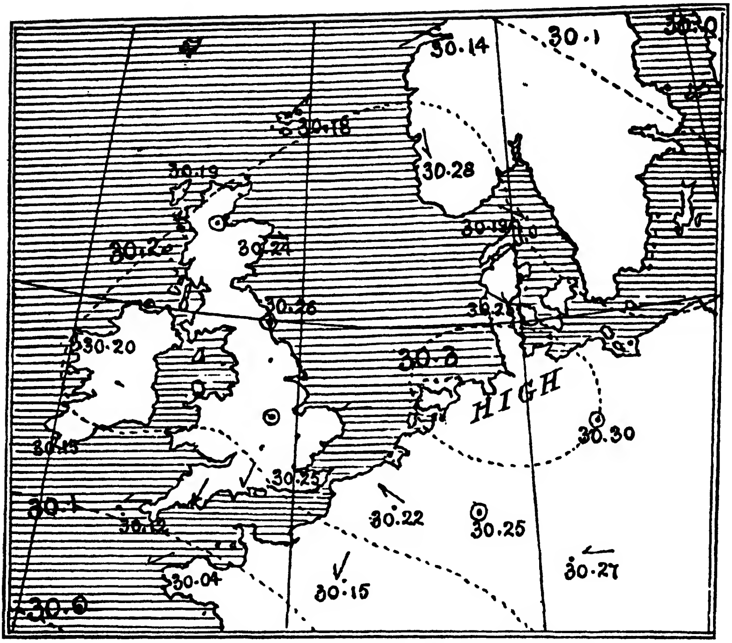


Fig. 75.—Anticyclonic system, 8 A.M. 29th September 1895.

The telegraphic reports received from places scattered over wide areas enable meteorologists to outline these 'isobars.'

The diagrams are copies of those issued by the Meteorological Office on 30th September and 3rd October 1895, and represent the break-up of a long spell of fine weather which lasted up to 29th September. On that day a high pressure area is seen over the British Isles (Fig. 75); in two days' time it gives place to a low pressure area (Fig. 76), with high winds and rain.

These instances are typical of the two main conditions which

occur, and serve for weather prediction. The high- or low-pressure areas appear to advance over the surface of the earth. An atmospheric area with a centre of least pressure is called *a cyclonic system* (Fig. 76).

In this the air revolves against the hands of a watch. The

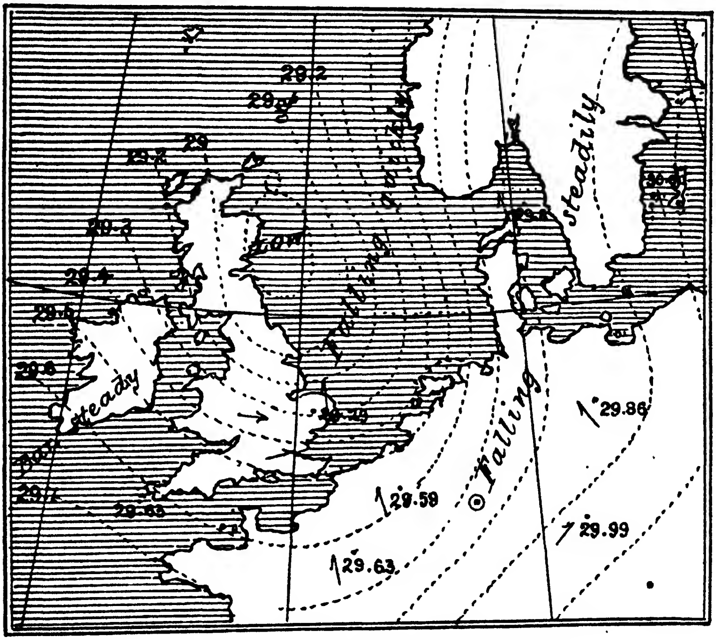


Fig. 76.—Cyclonic system, 8 A.M. 2nd October 1895.

lower layers of air are flowing in a spiral into the area of least pressure, and the air at that point is rising from the earth's surface. It expands and becomes cool; the water vapour is condensed and rain falls. The isobars are close together towards a low-pressure area, and the winds may be very violent.

In other cases areas appear with centres of greatest pressure. Round these the air revolves with the hands of a watch; they are called *anticyclonic systems* (Fig. 75), the isobars are not so close together—there is not such a high gradient. The winds

are not so strong, and the upper air is descending. Such conditions imply dry weather.

Several causes affect the barometric reading and, as they operate together, it is not easy to distinguish the effect of each cause.

The corrections which have been already referred to under *Reading and Correction of the Barometer* above having been made, the following variable elements remain, which may be classed together as meteorological conditions.

Some of these, the effect of the changes of temperature on the weight of the atmospheric column and the pressure of water vapour present in the air, must be discussed under the subject of Heat. If these could be eliminated and corrected for, there would still be changes of pressure. The atmosphere surrounding the earth is in a continual state of motion. If it could be made visible to an observer outside the earth he would see a complexity of waves crossing and recrossing one another, causing points of greatest and least pressure. Immense vortices would be seen in action, causing rarefaction or compression at their centres. The layers of the upper air would be seen moving in one way, while the lower layers move in another direction.

The motions of the air, considered mechanically, are modified by the rotation of the earth from west to east. Dove's law of storms is that the wind generally moves in the northern hemisphere in the direction opposite to the hands of a watch, the reverse being the case in the southern hemisphere. Buys-Ballot's law states that if the back be towards the wind the barometer will be lower on the left hand in the northern hemisphere, the reverse being the case in the southern hemisphere.

The diagrams (Figs. 75 and 76) illustrate the truth of the laws of Dove and Buys-Ballot.

The general directions for estimating the weather given by Admiral FitzRoy agree in the main with these principles (see HEAT, p. 364).

CHAPTER VII

PUMPS

Atmospheric Pressure Utilised—Siphon—Pumps—Common Pump—Lift-Pump—Force-Pump—Air-Chamber—Valves—Fire-Engine—Compressing Air-Pump—Diving-Bell.

The Atmospheric Pressure Utilised.—The universal pressure of the atmosphere was utilised long before it was known to exist. When a boy uses a 'sucker' he calls in its aid. A piece of leather is thoroughly softened in water and a string is attached to the middle of it. It will now fit closely on a stone or any smooth object; when the string is pulled a vacuum is left underneath and the atmospheric pressure presses the edges firmly against the stone, making them adhere sufficiently for the string to lift the stone. The limit to the force that can be applied is the product of the atmospheric pressure and the area of the leather, for this is the force which the pressure of the air exerts to make the stone follow the sucker.

Fountain inkstands, such as the 'isobath'; the common weather glass used in a cottage, a bottle half full of water inverted into a tumbler; water bottles for bird cages, etc., are all made to use the fact that liquid can be held up by the atmospheric pressure.

Siphon.—If a V-shaped tube be filled with water and the finger be placed on one end, it may be inverted without any of the water flowing out. If one end of it be immersed in a vessel of water, the other end being below the level of the

water, the water will flow out. Such a tube is called a *Siphon.* (Fig. 77). If any part of the siphon were raised higher above the surface than the height of a water barometer, the water would not stand so high in the tube, and a vacuum would be formed. This shows that the reason why liquid flows up a siphon tube is that the atmospheric pressure balances the liquid column, which reaches to the bend. Looking at the two columns as the two arms of a balance, the arm outside the vessel outweighs the shorter arm and flows downward. Were the liquid at the bend not to follow, a vacuum would be formed there, as mentioned above in the case of water if the bend is more than 32 ft. in vertical height from the surface. To any height less than this the atmospheric pressure forces water to rise, and to follow the longer column.

Fig. 77.—Siphon.

This may be experimentally proved by placing a siphon under an air-pump. A siphon discharging mercury, if placed under the receiver, is stopped when the pressure is sufficiently reduced. The experiment cannot conveniently be carried out with water, as a short column of water such as could be placed under a receiver causes so small a pressure.

Fig. 78.—Tantalus cup.

Tantalus Cup.—A siphon is concealed inside a figure of Tantalus, which is placed in a vase (Fig. 78). Water is poured into the vessel, and no sooner does it reach the top of the siphon and approach his mouth than the water all flows away through the bottom, leaving him as thirsty as ever.

Intermittent Spring.—If the outlet from a subterranean cavity rises before it falls into a valley, the cavity forms a reservoir of water and none will flow out till the water reaches the top of the bend; then all the water in the reservoir will be discharged. The cavity fills gradually by percolation through the soil and discharges at intervals, the result is an intermittent flow of water. Such a spring is the Fountain of the Virgin in Jerusalem, which flows three times a day in wet and once in dry weather (*Jerusalem*, Conder, p. 366). There used to be before A.D. 1630 a remarkable intermittent spring near Paderborn which

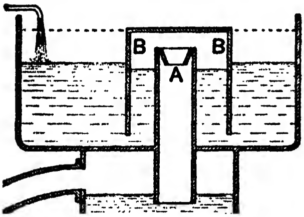


Fig. 79.—Flushing cistern.

Fig. 80.—Atmospheric pressure exhibited.

came out with so great force as to turn mills, but which stopped entirely for six hours daily; it ceased to exist about that date.

Flushing Cistern.—A small pipe runs continuously into a cistern (Fig. 79). When the water reaches the top of the exit-pipe A, instead of running down the sides, it is guided by a collar down the middle, taking air with it, and so rarefying the air in the cap B, which covers A. A siphon action then takes place, and the cistern is rapidly discharged, giving a strong flush of water.

Pumps.—Liquid may be discharged over the brim of a vessel or oven over a small hill by means of a siphon. But in the ordinary way force must be exerted to remove water from place to place, and this is done by means of a pump.

The atmospheric pressure was utilised in pumps even before it was known to exist; the manner of its application to the

removal of water will be shown by some experiments introductory to the subject of pumps.

When a tumbler brimful of water is covered with a card, the tumbler may be inverted, as shown in Fig. 80, without any liquid escaping. The atmospheric pressure exerts force on the card more than sufficient to overcome the weight of the water in the tumbler, for there is no atmospheric pressure downwards on the water.

A PIPETTE is a little pipe with which drops or small quantities of any liquid may be easily taken from a vessel. The

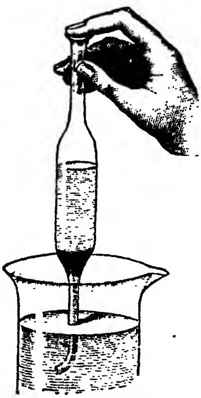


Fig. 81.—Pipette.

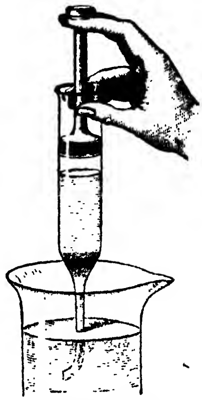


Fig. 82.—Syringe.

shape of it varies (Fig. 81) with the use which is to be made of it. When dipped into the liquid it fills to the level of the liquid; the finger is then placed on the upper end, and the pipette is removed full of liquid; the atmospheric pressure prevents the liquid from flowing out of the tube again. Much liquid or little, as desired, may then be allowed to come out of the tube by moving the finger and admitting air above.

A SYRINGE may be used for the same purpose. The glass syringe (Fig. 82) is not different in shape from the pipette, but a plunger fits tightly in the larger part of the tube. When this is raised the liquid flows into the tube much as when the pipette is withdrawn from the liquid with the finger on the end. The

syringe is then brought out, and whatever liquid is required is released by depressing the plunger.

The condition of things as the plunger is first raised should be noticed. In the figure it may be observed that the liquid is raised above the general level, but that there is a space between liquid and plunger. This is the air which was between the plunger and the liquid at the beginning. The pressure of this air, together with the pressure due to the column of liquid, is equal to the atmospheric pressure.

The Common Pump.—Suppose now that the barrel of the syringe be very long and the plunger be gradually drawn up it, the liquid does not rise so high as the plunger if there be some air below it, but a column of liquid follows the plunger. There is a limit to the height of this column; when the pressure due to the column is equal to the atmospheric pressure the liquid can rise no higher, nor can it rise so high if there be any air enclosed below the plunger.

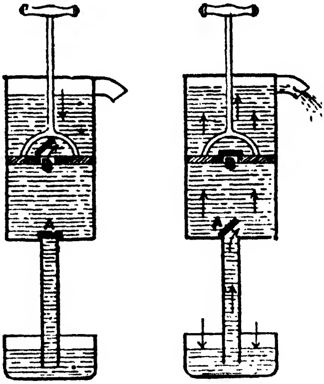
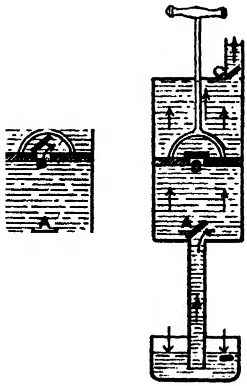


Fig. 83.—Common pump.

If the plunger be lowered again, the liquid descends and things are as they were at first. But suppose a door or valve A at the bottom of the pipe (Fig. 83), so that the liquid cannot descend, then neither can the plunger descend, except so far as there is air which it compresses. But if there be a door or valve B in the plunger or piston, the air and then the water flows through this as the piston descends. When the piston is raised again (Fig. 83), the valve B in the piston closes, and the liquid above it is lifted and flows over. Liquid then follows the piston without any air space. This arrangement is called *a Common Pump*. In the common pump there is a valve in the piston and

also at the bottom of the cylinder, both opening upwards. On the down-stroke the valve in the piston is opened, and on the up-stroke the valve at the bottom of the cylinder. As often as the piston is raised water is raised and flows out of the spout. But the pump will not draw water from a depth of more than 34 ft. Indeed it will not draw from so great a depth; the pressure of water vapour at 60° F. is that due to about 7 inches of water. No air can leak through piston or valve when there is water above the piston, and the pump should lift a column 33 ft. high. When a pump does not 'draw'—that is when piston or valves are leaky—water is thrown into the barrel, if any can be had, and this effectually stops the leakage. If there be a hole in the pipe below the piston the pump will not lift water at all, as air enters the hole when the piston is raised.

Lift-Pump.—When water is to be lifted to any great height, as the pump barrel cannot be placed more than about 30 ft. above the water, another arrangement is made. Instead of allowing the water to flow over, a pipe (Fig. 84) is led from the top of the cylinder, through which the water may be raised. There is a valve C at the bottom of this pipe which supports the column of water in the pipe during the down-stroke, but the use of this valve should not be misunderstood. The pump works just as well without it, as the water rests on the lower valve A during the down-stroke, but when the column of water is great the lower valve should be relieved of its weight during the downward stroke of the piston.



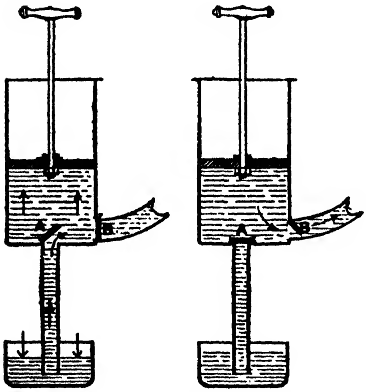
Down-stroke. Up-stroke.

Fig. 84.—Lift-pump.

There is no limit of the height to which water can be raised by the lift-pump, except the strength of the different parts. Cornish and other mines are drained by this class of pump, and

visitors often notice the massive beams and counterpoise requisite to carry the heavy rods.

Force-Pump.—A force-pump is like a syringe in that the plunger is solid, and liquid is forced out by the depression of the plunger. But the liquid leaves the syringe by the orifice of entrance, and this is not what is wanted in a pump. A door or valve A is fitted to prevent this, and another pipe leads from the bottom of the cylinder with a valve B opening outwards (Fig. 85). When drawing water from a depth the force-pump



Up-stroke. Down-stroke.

Fig. 85.—Force-pump.

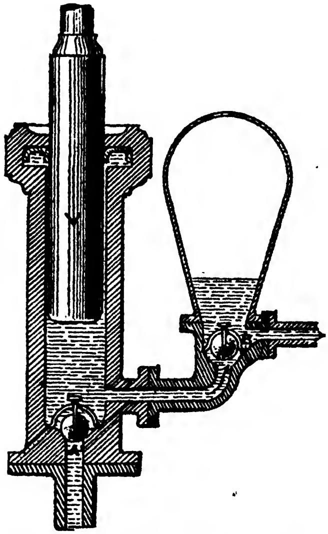


Fig. 86.—Force-pump with air-chamber.

acts as a common pump, and is limited by the height of the water barometer. The water can then be forced to any height, according to the strength of the pump.

If much force is to be exerted the plunger is made like the ram of a hydraulic press (Fig. 86), and is fitted with a cup leather to prevent leakage. Force-pumps are used for maintaining pressure in a system of pipes for transmitting power.

Air-Chamber.—A force-pump is almost always provided with an air-chamber. Water being practically incompressible,

any force applied suddenly to it when it has no means of escape causes an impulsive pressure throughout the whole, and may exert an extraordinary stress on the apparatus. An air-chamber (Fig. 86) is provided in which the water can compress the air and so allow the force to act through a little distance, expend its energy (MECHANICS, p. 54), and avoid an impulsive shock before which 'something must go.'

Valves are of different kinds according to the purposes for which they are required. The simplest valve is a door opening one way only, such as is shown in Figs. 83-85; this is called a '*clack valve.*' The valve shown at A in Fig. 86 is a '*ball valve.*' Air-pump valves usually consist of a strip of oiled silk stretched over a hole.

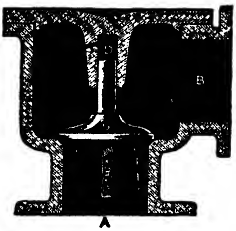
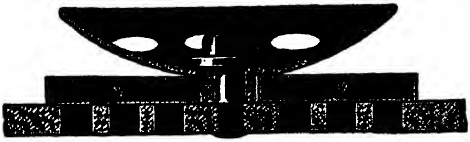


Fig. 87.—Common non-return valve.

Fig. 87 shows a common *non-return valve* used in steam machinery; A is the inlet and B the outlet; C is a conical valve which is guided by the 'feathers' F, so that it rises and falls without getting out of place. D is a guide which regulates the lift of C. Water or steam can flow from A to B but cannot return from B to A.

The india-rubber disc valve (Fig. 88) is also shown at U in Fig. 105. The india-rubber disc V closes the grating in the valve-seat S so that no fluid can flow downwards through it; the fluid can pass upwards by raising the india-rubber disc. The guard G prevents it from rising too far.

Fire-Engine.—What is required in a fire-engine is that water should be driven in a continuous stream through the hose and branch pipes to extinguish a fire. This familiar machine is illustrated by the lecture-room model (Fig. 89). The two plungers worked by the rocking lever draw the water through the valves A and B, and force it alternately into the air-chamber C through the valves A′ and B′, which prevent its return. The water at first enters the chamber faster than it can escape by



SECTIONAL ELEVATION.

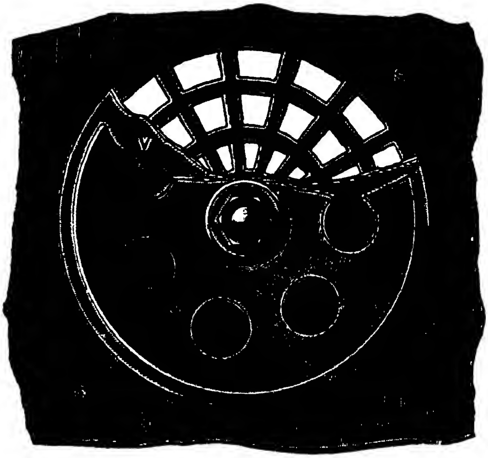


Fig. 88.—The india-rubber disc valve.

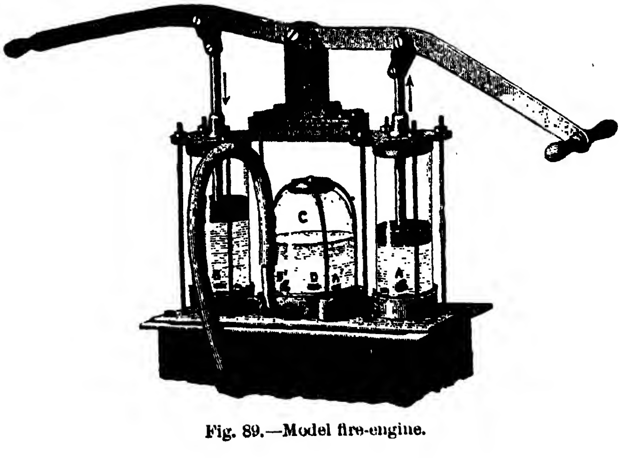


Fig. 89.—Model fire-engine.

the exit D into the pipe E; it compresses the air in the chamber, and so a continuous pressure is exerted on the surface of the water in C. By this means a continuous stream is driven out with considerable force instead of being driven out at each stroke of the pumps.

The Compressing Air-Pump is a force-pump used for air. The valves are arranged as shown in Fig. 85. Pumps for inflating footballs or pneumatic tyres have valves thus arranged, and the form of the pump is suited to the convenience of the user. The powerful engines used for compressing air for the caissons mentioned below, for operating an installation of pneumatic tools, for refrigerating engines, or for torpedo propulsion, blowing engines for blast furnaces or for large organs, all these have the same arrangement of valves. The scale and design of compressing pumps varies widely with the purpose for which they are intended.

Compressing pumps are also used to supply divers with air.

Diving-Bell.—When an empty tumbler is inverted over the surface of water some air is shut in the tumbler, which cannot escape so long as the rim is horizontal. As the tumbler is lowered into water the air is compressed into a smaller space and its pressure increased. If it were lowered to a depth of 34 ft. the air would be compressed into half its volume, the pressure of the air being doubled. It is in this way that a diving-bell is lowered into water to be employed in doing work under water; but to avoid the water rising in the bell a compressing air-pump is employed to force air through a tube into the bell. The bell is kept full of air at additional pressure due to the depth of the water. In building the Forth Bridge caissons (pronounce *casoons*) were constructed, 70 ft. in diameter, being in fact large diving-bells. These were floated out to their positions and sunk; air was pumped into them to drive the water out; excavators worked inside until they rested on an even basis. They were then filled with masonry and formed foundations to the piers. The pressure in the caissons at high water was nearly three atmospheres.

A diving-dress is also supplied with air by compressing pumps; the pressure in the helmet is greater than atmospheric pressure by that due to a column of water equal in height to the depth at which the diver is working—one atmosphere for each five fathoms.

CHAPTER VIII

Moving Fluids

Hydrokinetics—Head of Water—Velocity due to Head—Flow of Liquid—Shape of Flowing Jet—Vena Contracta—Falling Water—Pressure of Moving Fluids—Wind on Sails—Windmills—Ejector or Injector—Unbalanced Pressure—Barker's Mill—Work done by Moving Water—Turbines—Water-Wheels—Centrifugal Pump—Hydraulic Ram—Resistance to Motion—Propulsion of Ships—Power Necessary for Speed—Water Engines.

Hydrokinetics is the science of moving fluids. This is a subject of great difficulty and can only be slightly noticed here. Theoretical questions dealing with perfect fluids without friction are difficult; but the difficulty is enormously increased if the viscosity and friction of fluids are to be taken into account.

Head of Water.—The height of the surface of water above a water-engine is called the *head of water*. If the water is at rest, the head of water causes a pressure, as referred to in Chap. IV., increasing at the rate of one atmosphere, about 14·7 lb. per sq. in., for each 34 ft. of height. Pressure in water caused by pump, accumulator, etc. may consequently be described as a 'head of water' and measured at the same rate, which is equivalent to 2·3 ft. of head for each 1 lb. on the sq. in.

Velocity due to Head.—If water falls freely from a height it acquires a velocity in falling which varies as the square root of the height ($v^2 = 2gh$, Mechanics, p. 11), there being no friction. Again, if a hole be opened in the side of a vessel

containing water under pressure water flows out at a rate depending on the pressure. It appears likely, though it would be difficult to prove it theoretically, that these two facts must be connected. Torricelli devised an experiment for showing that this is so, and that *the velocity of efflux is that due to a fall from the height of the surface above the orifice.*

Flow of Liquid through an Opening—*Torricelli's Theorem.*—A tall vessel is supplied with water so regulated as to remain always at the same level. Small holes are made in the side of the vessel from which the water can flow horizontally, and these can be closed by rubber stops (Fig. 90). It is convenient not to have the holes vertically above one another. Each hole is opened in turn and the curve of the flowing jet is traced on a board which is brought near to it.


Fig. 90.—Torricelli's theorem.

Now in the illustration (MECHANICS, p. 18) a jet is shown rising nearly to the level of the surface of the water; the theoretical height and shape of the curve are altered by the friction and viscosity of air and water. But it was there experimentally shown that the velocity of the issuing jet is that due to a fall from the free surface, and that the curve is a parabola.

In Torricelli's experiment the question is limited to the shape of a jet issuing horizontally. The velocity of efflux $v = \sqrt{2gh}$, where h is the depth of the nozzle below the surface,

D (the horizontal distance after a time t) $= vt$,
F (distance of fall below nozzle . . . . .) $= \frac{1}{2}gt^2$.

From this we conclude that $D^2 = 4hF$.

When the product of h and F in any two curves is the same, the curves have the same value of D.

The forms of different curves of water falling from nozzles above one another at equal distances are seen in Fig. 91, the surface of the water being at AB, an equal distance above the highest. The intersections of the curves illustrate the condition $D^2 = 2hF$. The first curve (for which $h = 1$) meets the second (for which $h = 2$) where its $F = 2$ and the third where its $F = 3$. The second meets the third where its $F = 3$, and the third meets the fourth where its $F = 4$, and so on.

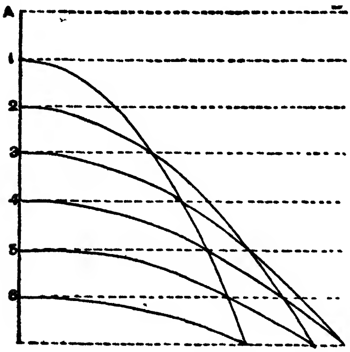


Fig. 91.—Curves of falling water.

Shape of a Flowing Jet.—When a hole is opened in the bottom of a vessel full of water, the water does not flow straight through the hole as if it were the end of a pipe. All the water in the vessel is trying to flow out at once like a crowd going through a door (Fig. 92). The effect of the combined motion of the particles of water before leaving the orifice is seen in the shape of the jet after leaving it. The outer particles flow in towards the axis of the column and the diameter of the jet diminishes as it leaves the orifice; it is not a cylindrical column of water which flows out.

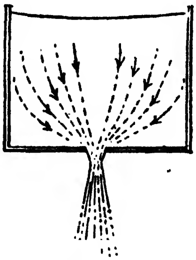


Fig. 92.—Vena Contracta.

Vena Contracta.—This narrowed stream is called the *vena contracta*. The illustration and description above refers only to a stream issuing from the bottom and falling vertically. This case is the simplest, but the 'vena contracta' is seen in the case of a jet issuing from an orifice in any direction. It occurs at a distance of about the radius of the hole from the opening. At this point the stream may be little more than half the opening in area of section.

It follows from this that the actual velocity of efflux

depends on the shape of the orifice or nozzle from which water flows.

If the orifice be made of the shape of the vena contracta (Fig. 93), the velocity is very nearly the velocity theoretically due to the head of water. Consequently it is usual to shape the issuing nozzle of branch pipes so as to contract the jet before it leaves.

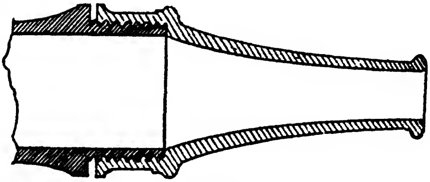


Fig. 93.—Branch pipe.

Falling Water.—The rate of flow from the vessel is measured by the product of the contracted area and the velocity of efflux. This product gives the volume of water flowing out in a unit of time. At a lower point of the stream the velocity of the falling water is increased. Looking at the falling stream as a column of water, the same volume of water must pass any point of it per unit of time, this being the amount that is leaving the vessel. Hence, at a lower point, the sectional area of the column must be less, and will go on decreasing until so small a section is reached that the stream breaks into drops.

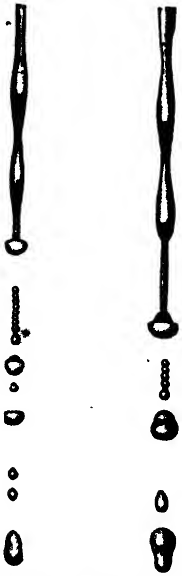


Fig. 94.—Falling stream.

The form of these drops was first made the subject of inquiry by the eminent physicist Savart. Their actual shape appears to be due to eddies in the liquid round the orifice. The effect of these is to set up pulsations in the falling column. Eddies, in fact, are set up in the falling water itself. In consequence of these, small drops appear to be inserted between the larger falling drops, and the stream has the general appearance of Fig. 94, when seen instantaneously illuminated by an electric flash. The shape of a falling stream is affected by the viscosity of the air;

so the pulsations of air causing sound have an effect on the jet. The sound pulsations cause the drops to rearrange themselves, so that the period of vibration in the stream may correspond with the period of the note sounded. These observations are more fully treated of in Sound.

The Pressure of Moving Fluids.—A fluid in motion exerts a pressure on a solid surface placed at right angles to its direction. When the surface is inclined to the current of the fluid, the pressure is still perpendicular to the surface but less in amount as the inclination to the line of flow becomes more acute. In both cases the amount of pressure depends on the velocity of the current. These principles may be illustrated, and proved in the case of water, by the following experiment (Fig. 95). A vertical tube open at the top is placed in a stream with its lower end bent into a horizontal direction so as to face the stream. The water rises in the tube to a height, a fall from which gives a velocity equal to that of the stream. This is really the converse of Torricelli's Theorem (p. 239) as to the velocity of an issuing stream—

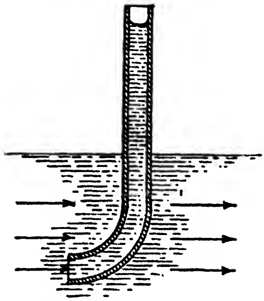


Fig. 95.—Pressure of moving water.

The pressure in a moving liquid varies as the head of liquid, and therefore as the square of the velocity.

The weight of the water in the tube exerts a pressure at its mouth, and the fact that such a column is supported shows that the flowing stream exerts an equal pressure there. This pressure is exerted on a surface placed at right angles to the direction of the stream. When the mouth of the tube is inclined at any other angle to the line of motion a smaller column of water is supported, showing that the pressure of a flowing liquid is less in amount as the inclination to the direction of flow is more acute.

The height of the column and the pressure on a surface would

be proportional to the square of the velocity only in the case of a 'perfect' liquid. In a real liquid the friction and viscosity give rise to eddies when it is in motion, and these affect the amount of pressure. In fact the pressure on a surface at right angles to a stream does in practice exceed the pressure due to the speed and the head of water causing it.

The pressure of moving water on a fixed surface is a subject of great difficulty, and it has been fully treated of by Lord Rayleigh.

Wind on Sails.—The velocity of wind varies from a hardly perceptible breeze moving perhaps a mile an hour to a hurricane with a velocity of from 80 to 100 miles an hour. The pressure exerted by the wind depends on its velocity, and may be as much as from 30 to 50 lbs. on the square foot.

What has been said of the pressure on a surface inclined at any angle to a stream applies to wind-pressure; it is greatest when a surface is at right angles to the direction of the wind, and less as the inclination is more acute.

In bridges or other structures provision must be made for strength to withstand the lateral pressure of the wind. But practical use is made of the pressure of the wind; it exerts force on the sails of a ship, boat, or windmill, and thus does work.

The pressure on the sail is due to the relative velocity of the wind and sail, and this fact gives rise to a sort of paradox, in that a boat goes faster across the wind than with it. This is best seen in the case of the ice-yachts used on the North American lakes and rivers. The force required to overcome the friction of their runners is very small, and they make very little 'leeway,' so the problem is simpler than in the case of a ship.

Suppose an ice-yacht with its sail set across the wind; when at rest the full force of the wind impels it, but as it acquires speed the force diminishes, being due to the relative velocity of wind and sail. When before the wind the yacht goes nearly as fast as the wind, but it cannot go faster than the wind.

When the yacht is going across the wind (Fig. 96) the force on the sail AB does not vanish, whatever the speed; and as but a small force is necessary to propel an ice-yacht, extraordinary speeds have been reached with a moderate breeze.

"Col. E. H. Sanford, the Commodore, declares that in his opinion the *Avalanche* and *Icicle*, and several others of the Hudson River fleet, have at times attained a speed of 90 miles an hour."

The same principles apply to the sailing of a ship or boat; the trimming of sails and the sailing so as to keep them full is an application of these principles by those who may be ignorant of them, but whose eyes and hands have been trained by experience, which itself is the basis of all scientific knowledge.

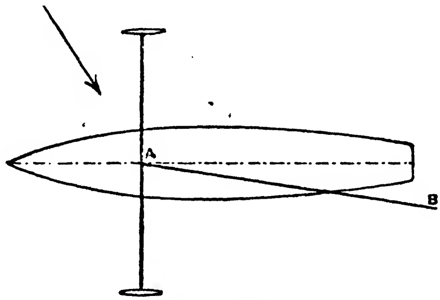


Fig. 96.—Ice-yacht.

Windmills are machines for utilising the movement of the air and compelling the winds to do work. There is the old-fashioned mill with its four arms; these are not flat, but shaped like part of a screw surface. Near the centre the sail is inclined at $\frac{2}{3}$ right angle to the axis of rotation, and it is less and less inclined until at the tip it is very nearly at right angles to the axis. Each part thus has the same propelling effect; for the part nearer the axis does not move so fast, and the speed of the sail changes the angle at which the wind strikes the sail. In the oldest mills a sail is spread on the arm, but this has given place to 'louvre boards,' like a venetian blind, which can be 'feathered' or turned at a greater or less angle to the wind, according to its strength. The old form of mill has given place to a circular pattern, in

which the fans are arranged radially between two concentric circles. These fans can also be 'feathered.'

Ejector or Injector.—In one way or another every one has met with some form of ejector or injector. In a scent diffuser or in some forms of ventilator, moving gas is seen carrying other vapour or gas with it, just as people may be carried, perhaps unwillingly, by a crowd entering a door.

The ejector is used as a pump to suck air or water out of a reservoir. The injector is used to force air or water into a reservoir. The diagram (Fig. 97) represents an ejector as commonly fitted in a steamboat for getting rid of the water from the bilges by blowing it overboard. This figure serves just as well to illustrate the elementary principle of the injector.

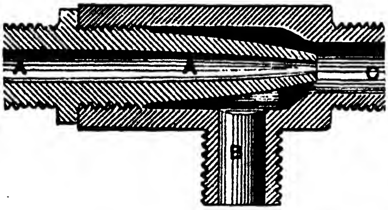


Fig. 97.—Injector or Ejector.

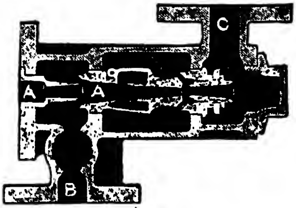


Fig. 98.—Injector.

In both of them the moving fluid passes through the middle of a hollow cone A, and carries with it into the pipe C other fluid which is supplied through the pipe B and conducted round the outside of the cone.

Both are used on some locomotives. In the ejector of the vacuum brake, steam is blown through the inside of the cone and carries with it the air round the outside, and thus the air is extracted from the brake-pipe. In the injector, steam blown through the middle carries water with it round the outside, which it forces into the boiler. The diagram (Fig. 98) represents a modern form of injector; the same letters are placed in positions corresponding with those in Fig. 97. It is a paradox that steam coming out of the boiler should force water into the boiler against a pressure actually greater by the depth of water

than the pressure of the steam. Some of the steam is condensed by the cold water, and the steam and water following to fill up the space acquire kinetic energy. This does work against the boiler pressure by forcing water to enter.

The ejector is used in Californian gold-mining in the form of what is called an *elevator*. Water is led from a great height into the tube A; its velocity, which is considerable, enables it to suck gravel with the water through the pipe B and deliver it through C. As much as 200 tons an hour are thus excavated.

Unbalanced Pressure.—If a vessel be full of water it will rest on a horizontal table, however smooth, the resultant pressure on the sides and bottom is a vertical force equal to the weight of the water in the vessel. If a hole be now opened in the side of the vessel, there is no pressure on that area, and the water flows out. The resultant pressure on the area of the hole was a force which is no longer exerted, and the part of the resultant pressure which was in equilibrium with it is a force impressed on the vessel, which, now unbalanced, must produce movement unless prevented by friction. The vessel will move in a direction opposite to that of the issuing stream, in consequence of the pressure on the side opposite to the opening. In the experiment (Fig. 99) a tall vessel is carried in a larger one and floats in a tank, the motion can then be seen.

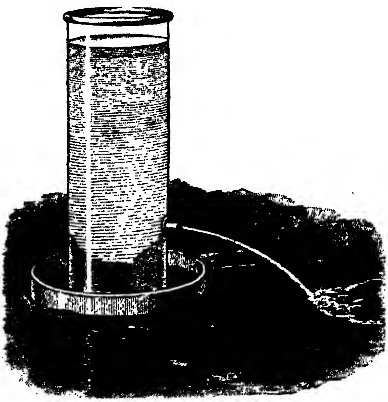


Fig. 99.—Unbalanced pressure.

Barker's Mill. — A closed tube C placed vertically, so that it can revolve on its axis, has two arms curved as shown in the plan (Fig. 100). Water flows into the vertical tube, and as it escapes by the curved arms the whole

is made to revolve; the pressure on the ends of the arms is unbalanced, and there is a resultant force in the direction of the arrows F. The tube C will revolve in the direction of the curved arrows.

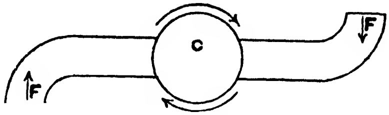


Fig. 100.—Barker's Mill.

If a stream flows steadily into the tube actuating two or more arms the machine will turn a grindstone or do other work. Messrs. Wrinch of Ipswich have lent a block showing the familiar 'sprinkler' used for watering lawns (Fig. 101). The


Fig. 101.—Sprinkler.

water is supplied through a hose at pressure and the revolving arms deliver it evenly in a fine spray over a wide area.

Work done by Moving Water.—The explanation of the movement in Barker's Mill refers rather to the pressure when the mill is at rest and motion is about to begin. When motion has begun, and water is falling through the tube and spouting from the openings, it is the work done by the moving water which has to be considered.

The product of the weight of the water falling in a minute and the 'head,' *i.e.* the height through which it falls, is the measure of the power available. If the machine were perfect, that is, if

there were neither liquid nor solid friction, this would give the power of the motor actuated by falling water.

Turbines.—The most usual form of water motor is the Turbine, which is a development of 'Barker's Mill' with its spouting arms. The problem before the water engineer is how to transfer the energy of moving water to energy of moving machinery with as little loss as possible in energy transformed into heat and into eddies in the water. This is effected in practice by using fixed guides which cause the water to impinge directly on the vanes or buckets of the turbine. The efficiency has been increased in this way by calculation and experiment in design so that the efficiency of modern turbines may be as much as ·8.

There are two principal forms of turbine—the turbine proper, in which the falling water acts much as wind does on a circular windmill on vanes round the whole periphery of the wheel, and the 'Pelton wheel,' in which the stream is delivered from nozzles on to buckets in the rim of the wheel, so that the water acts on a part of the wheel at a time, as a stream does on a water-wheel.

The Pelton wheel is used with a small flow of water from a great height, *e.g.* the Pike's Peak Hydro-Electric Company use the tremendous 'head' of 2417 ft., and the water issues from small nozzles at a velocity of more than 300 ft. per sec.

The Turbine proper may be understood by the figures opposite.

In the *Fourneyron* type (Fig. 102) the water flows through guides G, and is directed *outwards* on to the vanes V of the turbine wheel.

In the *Francis* type (Fig. 103) the water is directed inwards by the guides G on to the vanes V of a smaller wheel.

These figures are suggested by those in Molesworth's Pocket-Book, p. 536. The right-hand portion of each figure is thrown into perspective, so that the guides and vanes may be seen. The plans show how the guide leads the water directly on to the vane. a is the guide angle, β the entrance angle, γ the exit angle.

In the *Jonval* type the water continues to fall *downwards*, and is directed by the guides on to the vanes of a wheel below them.

Switzerland abounds in power stations operated by its glacier-

fed streams, but the power distribution at Niagara is the biggest thing of the kind at the present time.

It is estimated that the available power of the Falls of Niagara at mean level is about 4,000,000 H.P., assuming 222,000 cub. ft. of water to fall 160 ft. in each second. The total utilisation of power projected amounts to 650,000 H.P., of which 415,000 are taken off on the Canadian side.

The Niagara Falls Power Company, the pioneer of the large schemes, diverts part of the river above the Falls into a canal

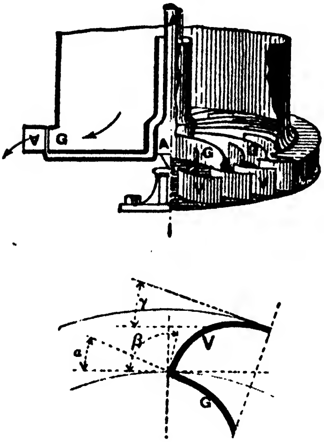


Fig. 102.—Turbine, Fourneyron or outward flow.

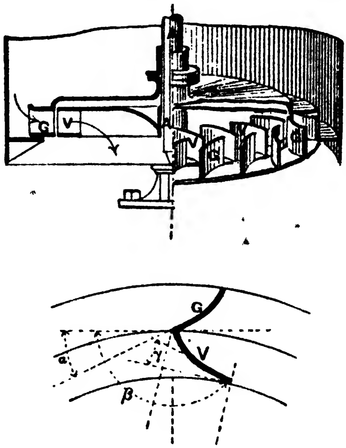


Fig. 103.—Turbine, Francis or inward flow.

on the American side, and turbines are placed 140 ft. below this canal side by side in two wheel-pits, slots cut in the rock. There are ten turbines in one pit and eleven in the other of the 'outward' flow type, each developing 5000 H.P., twin turbines, with holes in the upper guide disc, so that the unbalanced thrust on the upper wheel carries the weight of the shaft and wheels.

Water-Wheels.—The turbine supersedes the old water-wheel. Still cases occur when water-wheels can profitably be used. They are of two principal forms—*overshot wheels*, in which the water runs into buckets, which are emptied as the wheel turns

round. The weight of the water on one side of the wheel is thus the force by which the wheel is turned and work done. *Undershot wheels* have radial floats like the paddles of a steamer. The wheel fills up a channel down which the water is flowing with considerable velocity. The momentum of the water causes pressure on the floats, as in the turbine.

These forms are so well known that no illustrations are necessary. An overshot wheel is more suitable when the fall is great and the amount of water small. The diameter of the wheel is nearly the height of the fall, so that such a wheel may be of great dimensions, as much as 70 ft. in diameter. The efficiency may be as great as ·7 or ·8. An undershot wheel is suitable for a position where there is a large supply of water with a low fall. The efficiency has not been found to be greater than ·6 in general.

Centrifugal Pumps are reversed turbines. In a turbine the flow of water develops power by rotating a shaft; in a centrifugal pump power applied by the rotation of a shaft causes a flow of water. A centrifugal pump is usually of the form illustrated (Fig. 104). Water is admitted to the centre of the pump, and getting into the spaces between the vanes, is thrown off by centrifugal force against the casing which surrounds them, and which has an outlet for the discharge of the water.

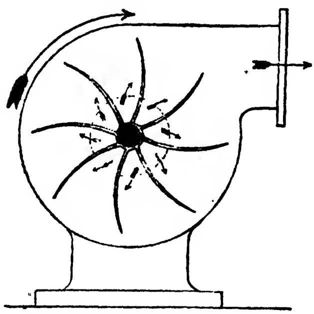


Fig. 104.—Centrifugal pump.

Centrifugal pumps are very much used in engineering works, for clearing coffer-dams or docks, also in machinery for circulating cooling water through the condenser tubes. They are very powerful, and they are very simple, as they have no valves to get out of order. The general idea has been hitherto that they were essentially low lift pumps; but of late years centrifugal pumps have been employed in lifting water up to consider-

able heights. This is effected by having a number of wheels or discs, the water being dealt with in stages (p. 255).

Air fans for ventilating purposes or for any purpose where air is to be circulated are usually centrifugal pumps.

The Hydraulic Ram, invented by Montgolfier, raises water to a height greater than that from which it has fallen, and so is somewhat of a paradox.

Water when falling freely acquires momentum and kinetic energy. The shock which occurs in a pipe when a tap is sud-

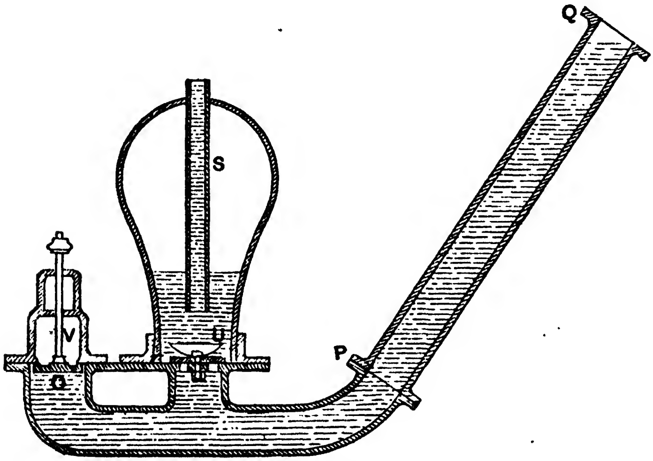


Fig. 105.—Hydraulic ram.

denly closed and the momentum is 'destroyed' is a matter of familiar experience.

In the hydraulic ram, shown in Fig. 105 with the parts at rest, water is allowed to flow freely down an inclined pipe PQ, and to escape through an opening O; this opening has a heavy valve V, and the water continually presses on this as it escapes. When the velocity of the water is sufficiently great the pressure of the moving water on this valve lifts and closes it. The column of water in PQ has a certain kinetic energy, which is converted into work in closing the valve V and lifting the

column of water in the pipe S through a certain height. When this work has been done the water is reduced to rest, the valve V drops, and water begins to flow again down PQ and through O.

Suppose that from the time that V drops and motion begins until V rises a column of water of length PQ flows down the pipe; then the energy developed during the time is that due to the fall of that mass of water through the height between the levels of P and Q. This energy is expended on raising the whole mass of water in the pipe S through a certain height. For the efficient working of the ram the pipe S should neither be long nor large.

This ingenious little pump will go on working day and night without attention. The only thing that is required for its efficient use is a fair supply of water falling through some feet.

There is a parallel between the actions of the injector and the hydraulic ram which is worth considering, as they are both paradoxical in that they utilise pressure to do work against a higher pressure. The escape of water to waste through the valve O, and the vacuum formed in the injector by condensation, both give the following fluid potential energy, ability to yield to pressure and so acquire kinetic energy, which does work.

Resistance to Motion of a solid body through fluid.—What has been said of the pressure exerted by a moving stream on a solid immersed in it applies to the resistance which a fluid offers to the movement of a solid through it. But the subject may be approached from a different point of view.

When an immersed solid moves, some water is displaced and a change of momentum takes place. Take as an example the blade of an oar, which in statics is ordinarily treated as the fixed point or fulcrum of the oar. What really happens is somewhat as though the blade rested against a heavy mass suspended and free to move. The blade has to set in motion a considerable mass of water if it is to move; the change of momentum of this mass set in motion in one second is the measure of the force which we call the 'resistance' of the water to the blade.

The momentum imparted to a given mass of water in a second varies as the velocity imparted; again, if the blade goes twice as fast through the water it meets with twice as much water, and so the mass of water displaced in one second also varies as the velocity of the solid which displaces it. Therefore the change of momentum per second due to a solid body moving through a fluid varies as the square of the velocity. It is thus seen that the resistance offered by water to the movement of a solid through it is proportional to the square of the velocity.

This conclusion is the same which was reached when considering the pressure of moving fluids.

Propulsion of Ships.—The resistance to be overcome in propelling a ship is partly due to the change of momentum of the water displaced in one second, the effect of which is seen in waves, eddies, and currents produced, and which has been proved to be proportional to the square of the speed. It is also partly due to the friction or 'skin resistance' to movement in a viscous fluid, by which kinetic energy is transformed into heat. Friction between a solid and a fluid is believed to increase as the square of the relative speed.

That both of these resistances must be considered is seen in the familiar example of towing a tapering spar. Less water would be displaced if the spar was towed the thinner end first, but the friction at every point along the spar is considerable when it enters like a wedge and makes the water move rapidly along its surface. It is therefore easier to tow a spar the thick end first; the water then follows it and the relative velocity at any point of the surface is smaller.

In designing a fast vessel the lines are shaped so that the entering surfaces may follow the line of motion of the water as it is displaced, and so the disturbance of water may be less, while at the same time it should be the object to diminish friction. A good design may diminish the resistance at a given speed, but it does not alter the fact that the resistance increases with the square of the speed.

The experiments of the late Mr. W. Froude of Chelston Cross

led to many improvements in design as well as to experimental proof of the truth of the principles which have been described. Constructing models of paraffin and wax, he observed the resistance to their motion through the water and the waves which they caused, and was able to indicate faults of design which could be remedied. His method has been adopted by the Admiralty, and is used in their experimental tanks at Portsmouth.

Power Necessary for Speed.—The work done in propelling a ship is the product of the resistance overcome and the distance through which it is overcome, and the horse-power necessary depends on the work to be done in a given time.

The resistance varies as the square of the speed, and the distance through which the resistance is overcome in one second varies directly as the speed. Therefore the horse-power necessary to propel a vessel varies as the cube of the speed.

This accounts for the great increase in horse-power necessary to drive a vessel at a higher speed. If engines developing 1000 H.P. can drive a vessel 15 knots, it would require engines developing 8000 H.P. to drive the same vessel at 30 knots.

Water-Engines.—In Chap. II. Transmission of Power by Fluid Pressure was referred to as an illustration of the Transmissibility of Fluid Pressure.

Suppose a pump delivering water uniformly into a pipe or channel which is full; if the pipe varies in area of section, the amount of water flowing across any section in a second is constant, since that is what the pump is delivering. If the pipe be conical, increasing in size, the water will move more slowly as the pipe increases in section—the kinetic energy will be diminished.

But by the principle of the Conservation of Energy (p. 41) the sum of the potential and kinetic energies is constant; so if the kinetic energy of the water decreases, the potential energy, that is, the "head" or pressure, increases. So we see that as the channel or passage expands and the water moves more slowly, its pressure increases; conversely, in a narrower passage, the pressure is less.

This principle is used in the modern centrifugals (p. 250). After the water has been driven by the first impeller at a high

velocity against the casing, expanding passages guide it back to the axis. As the guide passage expands, the water goes slower and its 'head' increases so that it enters the second impeller at the same velocity as the first, but at a greater pressure. Each successive impeller gives the water a velocity which is converted into pressure.

In this way a very high pressure is given to the water, and it may be delivered at a very great height. Two such turbine pumps in a Welsh pit deliver 1350 galls. per min. each against 1645 feet.

There is, however, an important consideration with regard to the transmission of energy by water pressure, and that is 'loss of head'—the diminution of pressure through causes involved in the distance of the water-engine from the source of energy.

These causes may be classed as follows:—(1) Friction in pipes; (2) passage from a smaller into a larger pipe; (3) passage from a larger into a smaller pipe; (4) passage through a diaphragm or valve; (5) bends in pipes.

The first of these causes is the only one which need be considered here, for the others must be avoided as much as possible in the design.

The friction of liquids seems to be independent of the pressure, but to vary as the area of the surface wetted and as the square of the speed. To secure efficiency under these conditions, the piston speed of hydraulic engines is small, and the pressure in the pipes is great. If rapid movement is required from the machine, it is attained by the use of toothed gearing, or by one of the 'mechanical powers.' In hydraulic cranes a reversed purchase (MECHANICS, p. 91) is used; the ram moves slowly, exerting a great force, thus lifting a moderate weight more rapidly.

By this means the friction of the water is avoided; but the friction of parts which work very slowly is great, it is therefore necessary to hold a balance between the two. As a matter of experience, it is found that a hydraulic engine works most profitably when the useful work given off is $\frac{2}{3}$ of the work which the source of energy is supplying.

A hydraulic engine cannot race; it contains within itself its own brakes.

HEAT

CHAPTER I

Nature and Effects of Heat

Sensations of Heat and Cold—Temperature—Amount of Heat—The Thermometer—Effects of Heat—Chemical Effects—Electrical Effects—The Thermopile—Change of Volume—Change of State.

Sensations of Heat and Cold.—We use the eye as a test of light and colour, and we rely on the ear as a judge of sound; but when we come to the subject of heat, our sensations afford us very misleading evidence.

Our sense of feeling affords us no guide even as to the simple question, whether two bodies are equally hot. If a tinman's soldering iron be left in a hot oven, we can take it by its wooden handle, while the copper end of it could not be touched; yet one may be nearly as hot as the other.

Our senses may deceive us in a more surprising manner. If the hand be placed on a gun barrel suddenly and removed as quickly, because it feels burned or scorched, one cannot tell by the feeling whether the barrel is at a dull red heat or many degrees below the freezing-point; the hand feels burned, that is all.

And there is a yet more subtle deception which heat can practise on the eye. Suppose we see two copper dishes on a balance, the one containing mercury and the other an equal quantity of water by weight and both at the temperature of the open air. We now place them in a dish of boiling water and leave them there until we feel sure that the one is as hot as the other. They have both the same mass; they have been raised through the same range of temperature; they appear

to have both been equally heated; yet we shall learn later that the water has received thirty times as much heat as the mercury.

Our senses are, in fact, not qualified to serve as guides in the difficulties which surround this subject without some more truthful tests than they supply. In the course of observing the effects of heat, we shall be able to find some tests which are so accurate and regular that they are suitable for use in measurements, and will guide our senses to correct answers. So, though the question, What is heat? is a natural one to ask, it is not one to which it is wise at first to attempt to give an answer. It will be better first to ask, *What are the effects of heat?*

When the effects have been arranged, we shall have material to aid us in giving an answer to the apparently simple question, What is heat?

Temperature.—It is a matter of observation that a hotter body can communicate heat to a cooler body. For example, a bottle of jelly is placed in a basin of hot water to be warmed; the jelly is poured out into a mould, and this in turn is placed in a basin of cold water to be cooled. Heat flows or passes from the water to the cooler jelly and from the jelly to the cooler water.

Temperature is that condition of a body on which its ability to communicate heat to, or to receive heat from, another depends.

Two bodies are at the same temperature when being in contact, neither can impart heat to the other.

When a body is at a higher temperature we speak of it as 'hotter,' and when at a lower as 'colder' than another.

Temperature has been compared to what is called 'level' in Hydrostatics. If two reservoirs are joined, water flows from the one which is at a higher level to one which is at a lower level. If both be at the same level no water will flow, even though one be a teacup and the other the ocean.

Amount of Heat.—The amount of heat that can flow from one body to another depends on the mass of the bodies as well

as on the difference of their temperatures. We shall see later on that it also depends on the material or substance of the bodies. A lighted match is a good deal hotter than boiling water, yet the flame of a match may be extinguished between the fingers with impunity, while the fingers would be scalded if placed in the water, because it imparts a greater amount of heat to the fingers than the flame can.

The Thermometer is an instrument used to measure and indicate temperature.

Effects of Heat

The results of imparting heat to bodies are called shortly the effects of heat; these may be divided into—

1. Chemical effects—
   (*a*) combination, such as *combustion*.
   (*b*) decomposition.
2. Electrical effects, such as are shown in the *thermopile*.
3. Change of volume—
   (*a*) of gases, as in the *air thermometer*.
   (*b*) of liquids, as in the *liquid thermometer*.
   (*c*) of solids, as in the *metallic thermometer*.
4. Change of state—
   (*a*) of solid into liquid, as in the *ice-block*.
   (*b*) of liquid into gas, as in the *boiler*.

The effect of excessive heat on all animal and vegetable tissues is destructive.

1. Chemical Effects.—When a body is heated its molecules are more ready to alter their chemical composition. Metals combine more readily with the oxygen of the air and 'rust' when they are heated. Some gases combine with one another if raised to a high temperature. Combustion is an effect of high temperature; a certain temperature is required to start it. A fire may be smouldering and giving out gas, which does not burn; if left to itself the fire would go out, but the small flame of a match affords the high temperature necessary for the

combustion of the gases, and the whole bursts into brilliant flame. Certainly heat is evolved, but heat is required to begin it.

Another chemical effect of heat is that, when heated, a compound body has a tendency to separate into elements. As an example, mercuric oxide (red oxide of mercury) splits up when heated into mercury and oxygen.

2. Electrical Effects.—There is obviously a close connection between heat and electricity. The effect of a flash of lightning in setting fire to stacks and farm buildings is a familiar one. Conductors, through which an electrical current is passing, are heated, a fact which is used practically in incandescent electric lighting.

But while the production of heat by electricity is very familiar to us, the reverse, viz. the production of strong currents of electricity by the direct action of heat, without the intervention of an engine, has not yet been practically effected.

Small currents are caused when a junction of two dissimilar metals is heated. The presence of these currents can be detected by the deflection of a magnetic needle. This subject is fully dealt with in ELECTRICITY, Chap. VIII., but it is mentioned here because of the apparatus for testing temperature, by observing these currents.

Thermopile.—Several pairs of metals are grouped in such a way that their alternate junctions are exposed on the face of a thermopile. Such an arrangement is shown in the engraving (Fig. 1). The face of the thermopile at A shows 42 metallic junctions on which the radiation to be measured falls. A hollow cone C is shown as about to be fitted on this face to protect it from any rays but those to which it is directed. Two wires lead from the terminals of the thermopile to the galvanometer B, a magnetic needle suspended and carrying a small mirror. The light from a lamp D is reflected from the mirror on to a scale, and the spot of light on the scale shows the deflection of the needle to right or left.

Change of temperature is what is shown by the thermopile,

radiation from a hotter body causing a deflection of the spot of light one way, and radiation to a colder body deflecting the spot in the opposite direction. The wires may be led to either binding screw of the galvanometer, so that a rise of temperature may deflect to *right* and a fall to *left*, or *vice versâ*, as preferred. In small changes, the distance which the spot moves may be considered to be proportional to the change of temperature, and in this way the instrument may be used to measure small differences of temperature.

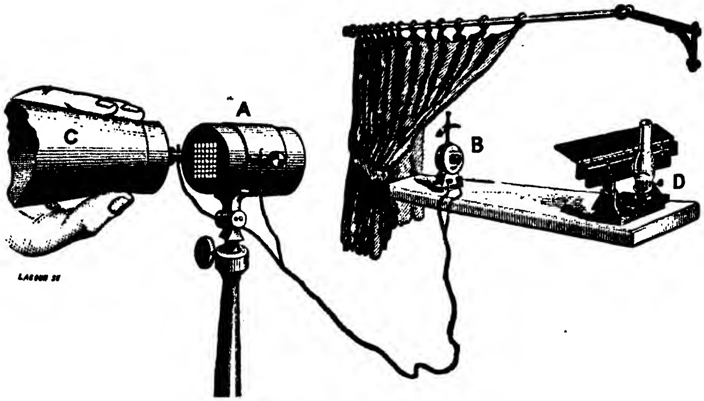


Fig. 1.—Thermopile.

The thermopile will be referred to henceforth as an instrument for detecting changes of temperature.

3. Change of Volume.—With few exceptions all bodies, whether solids, liquids, or gases, increase in volume when they are heated.

4. Change of State.—Most substances are capable of existing in the three states: solid, liquid, and gas. Change of state is one of the effects of the addition of heat to a body.

The change of volume and change of state will form the subject of separate chapters.

CHAPTER II

Effects of Heat—Expansion

Gases

Charles's Law—Air Thermometer—Absolute Air Thermometer—Scales of Temperature—Graduation—The Absolute Scale—Coefficient of Expansion—Consequences of Expansion of Air—Convection Currents—The Trade Winds—Land and Sea Breezes—Monsoons—Ventilation—Refrigerator Engines—Liquid Air.

If an empty bottle is corked and a hole bored through the cork, when it is held in a pan of warm water bubbles of air are seen to come freely from the cork. The bottle though called empty is full of air, and the air expands or dilates when heated. Fill the bottle with coal gas by holding it for some time over a gas burner; the gas is lighter than the air and displaces it. Now if the bottle be corked and warmed as above the bubbles of gas escape from a hole in the cork. These experiments show the effect of heat in causing gases to expand.

Five or six common wine bottles are filled with oxygen, hydrogen, carbonic acid or other gases, one being filled with common air. They are corked and provided with glass tubes through the corks, the glass tubes being bent so that when the bottles are laid in a trough of water the tubes rise vertically (Fig. 2); the tubes each have a drop of mercury in the bend.

The trough is heated by a steam jacket, and as the bottles are heated the mercury is seen to rise in the tubes, showing that each of the gases expands. If the water in the trough be well stirred, all the bottles and their contents must be at the same

temperature. The drop of mercury in all the tubes is seen to rise equally; and this shows that all these gases expand equally for the same rise of temperature.

Expansion as an effect of imparting heat is seen most simply in the case of gases. For a given rise of temperature they expand more than either liquids or solids; they expand with

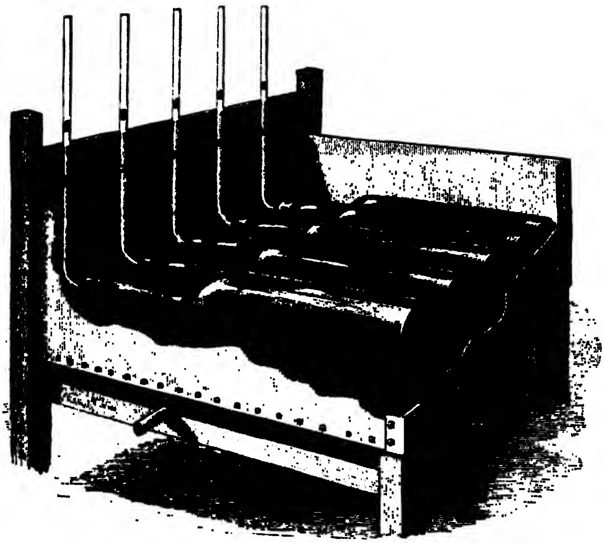


Fig. 2.—Expansion of gases.

perfect regularity, and all gases expand nearly in the same ratio to the rise of temperature.

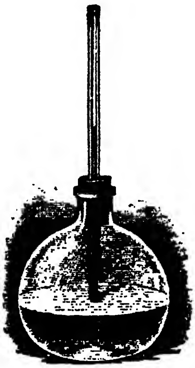
Charles's Law.—The law of the expansion of gases when heated was discovered, though not published, by Charles in 1786. Subsequently it was published by Dalton in 1801, and by Gay-Lussac independently in 1802; thus unfortunately the law is known by the three names, as patriotism may dictate. More than a century before this Galileo had seen that the expansion of air provides a means of making an instrument for measuring temperatures, and Boyle had used it in his experiments.

The observations of Charles showed him that *the volume of a*

given mass of air increases for each degree of rise in temperature by a constant fraction of its volume at freezing-point, provided the pressure be constant—the fraction being 1/273 *Centigrade, and* 1/491 *Fahrenheit.*

As Charles was the first who discovered the law, it is now usually known by his name.

The Air Thermometer.—This simple indicator of temperature was used by Galileo and Boyle in the form shown in Fig. 3. A bottle partly filled with coloured liquid is closed with a cork and sealed. A fine tube partly filled with the same liquid is sealed in the cork. The increase in the volume of air



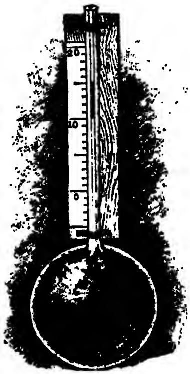


Fig. 3. Early thermometers. Fig. 4.

in the bottle, when heated, is shown by a corresponding rise of the liquid in the tube.

Another form used by them is shown in Fig. 4. A large bulb is connected with a fine tube; the air in the bulb having been heated the end of the tube is immersed in mercury as the bulb is cooling; the contraction of the air admits a little mercury into the tube, which is then left open. The expansion and contraction of the air in the bulb causes the drop of mercury to rise and fall. The temperature is indicated by the position of the mercury on the scale.

For small changes of temperature air thermometers such as these are very sensitive. The large volume of the bulb and

bottle give a large movement of the mercury in a fine tube. There is, however, the disadvantage that changes in the pressure of the air affect the reading.

Air and hydrogen thermometers are much used in scientific work. The International Committee (1887) selected the hydrogen constant-volume thermometer, in which equal increments of temperature correspond to equal increments of pressure (see p. 270).

Absolute Air Thermometer.—This form of air thermometer, if not so sensitive as those just described, is worthy of attention, in connection with the absolute scale of temperature referred to hereafter. A glass tube with fine bore uniform throughout is closed at one end, after care has been taken to ensure that the air in it is dry. The tube is heated above the temperature of boiling water, and while cooling, its end is plunged for a

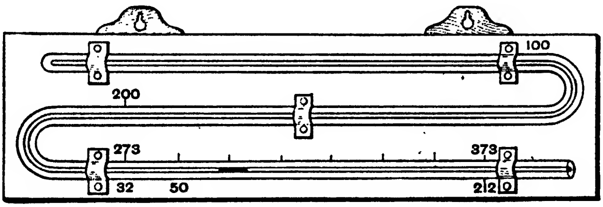


Fig. 5.—Absolute air thermometer.

moment in mercury (Fig. 5). A small drop of mercury is drawn into the tube as the air contracts, and seals the air then in the tube. The end is left open, and if the tube be horizontal the air in it is always at atmospheric pressure.

Later on (pp. 314, 331) it will be observed that there are two phenomena, the freezing and boiling of water, which take place at definite temperatures under the same pressure. These can be used as standard temperatures.

Scales of Temperature.—In Newton's scale of temperatures (1701) the melting-point of snow was taken as zero, and the temperature of the human body as 12. This Fahrenheit varied in 1721 by choosing as zero the lowest temperature he reached by a freezing mixture of ice and salt. First he called the normal temperature of the body 8°; subsequently 96°, and freezing-point 32°.

The boiling-point of water being the same for the same pressure, its value as a second standard temperature was soon recognised. This temperature was placed at 212° of Fahrenheit's scale, the freezing-point remaining at 32°. This position of the boiling-point defeats Fahrenheit's original plan of 96° for the human body; its normal temperature being 98·4° when the interval between 32° and 212° is equally divided.

The suggestion to establish the freezing-point at zero and the boiling-point at 100° was made by Celsius in 1742, and has been adopted exclusively in France, and for scientific purposes, under the name of the Centigrade scale.

Réaumur divided the space between freezing- and boiling-points into eighty parts. This scale is used in Germany and Russia, but no further reference will be made to it here.

Unfortunately, it is necessary to retain Fahrenheit's scale as well as the Centigrade in an English book. For engineering, meteorological, and commercial purposes the Fahrenheit scale is exclusively used, and great annoyance would be caused by its omission.

To Graduate the Air Thermometer.—(i.) To ascertain the freezing-point. The tube is placed in and well covered with pounded and melting ice, and when it has remained long enough to take up the temperature of the water in contact with the ice, it is withdrawn sufficiently to note the lowest point reached by the mercury. A scratch is made on the glass at that point.

(ii.) To ascertain the boiling-point. The tube is placed in a current of steam from boiling water. The apparatus described on p. 332, for use in ascertaining the height of mountains by boiling water, is suitable for this purpose. Care must be taken to mark the highest point reached by the drop of the mercury at a time when the tube is at the temperature of the steam. As the volume of air is proportional to the pressure, and the air thermometer measures change of volume of air, changes in atmospheric pressure will always affect it. The boiling-point is also affected by pressure. If possible it will be well to choose

a day for the experiment when the barometer stands at 760 mm. (29·92 in.), the fixed points will not need correction for pressure. The thermometer, with its two marked points of freezing and boiling, should be mounted horizontally on a scale.

The Absolute Scale.—The two standard points on the air thermometer—freezing and boiling—being marked as 0° C. or 32° F., and 100° C. or 212° F., the space between these can be divided into equal divisions or degrees. If the bore of the tube is uniform and the height of the barometer continues the same, the movement of the drop of mercury over these equal spaces will register equal changes of temperature.

If now the graduations be carried below the freezing-point evenly throughout the length of the tube it will be found that 273 of the divisions C. and 491 of the divisions F. reach the bottom of the tube.

It will be noticed that these numbers correspond with the fractions observed by Charles, and it is on this ground that this form is called the absolute air thermometer. For if the temperatures be reckoned from the bottom of the tube, and called absolute temperature, so that freezing-point is 273 C. *absolute* (or 491 F. *absolute*), and boiling-point is 373 C. *absolute* (or 671 F. *absolute*), we get the remarkable result that *the volume of a given mass of air, at constant pressure, is proportional to its absolute temperature.*

The conclusion apparently arrived at is that if air could be cooled down to 0° *absolute* it would have no volume. The law does not hold good in the neighbourhood of this point of absolute zero. The experiments of Professor Dewar with liquid and solid air show that below a temperature of about − 200 C. air occupies a larger volume than that proportional to the temperature.

Charles's law of the expansion of air when heated is true for all gases, except when they are near to their points of liquefaction.

The volume of any gas at constant pressure varies as its absolute temperature.

By a combination of Boyle's law (see HYDROSTATICS, p. 171) with Charles's law, we have the following comprehensive law :—

For all gases, when not near to liquefaction, the product of the volume and pressure is proportional to the absolute temperature.

The following example will illustrate its application :—

The volume of a gas at 10° C. and under a pressure of 27·99 inches of mercury is a cub. ft. ; what will be its volume at zero and under a pressure of 30. ins. of mercury ?

The vol. of the gas at 10° C. (283 *abs.*) = 1 cub. ft. ; the pressure 27·99.

" " at 0° C. (273 *abs.*) $= \frac{273}{283}$ cub. ft. ; the pressure 27·99.

The vol. of the gas at 0° C. and 30 inches pressure $= \frac{273}{283} \cdot \frac{27{\cdot}99}{30{\cdot}00}$,

$= {\cdot}9$ cub. ft. nearly.

Coefficient of Expansion.—The volume of a given mass increases for each rise of temperature of 1° by a fraction of its volume at the standard temperature. This fraction is called the *coefficient of expansion* in volume or *of dilatation.*

The coefficient of expansion of gases increases the nearer they are to their point of liquefaction.

COEFFICIENTS OF EXPANSION OF GASES FOR 1° C.

Hydrogen	·00366	Carbonic Acid	·00371
Air, Nitrogen, Oxygen	·00367	Nitrous Oxide	·00372

Those given in the first column are far from liquefaction at ordinary temperatures and pressures, and their coefficients are sensibly the same. The fraction 1/273 is ·00366, and 1/272 is ·00367, and the fraction 1/491, which is the coefficient for 1° F., is ·002 (approximately).

DIFFERENTIAL AIR THERMOMETER.—A difference in the temperature at two places near to one another may be made evident by a combination of two air thermometers. Two large glass bulbs are connected by a U-shaped tube of fine bore. The

lower part of this tube is filled with mercury (Fig. 6). If the mercury stands at the same height in both the vertical tubes, an equal quantity of air is sealed in each bulb.

If the temperature of one bulb rise above that of the other, the air in it expands, and by forcing the mercury down compresses the air in the other. A scale is used to indicate these changes of volume. This form is due to Sir John Leslie, who made use of it in his experiments on Radiation (see p. 398).

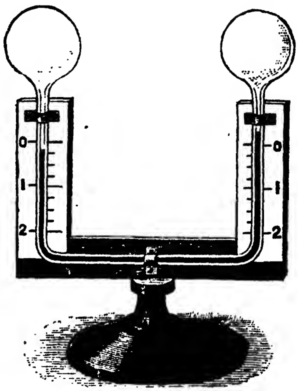


Fig. 6.—Differential air thermometer.

The differential air thermometer is often called a *thermoscope*, and the bulbs are placed in different positions, according to the nature of the experiment or investigation for which the instrument is required (see Figs. 75 and 78).

Consequences of the Expansion of Air

When air is heated and expands, it becomes less dense and of smaller specific gravity; any heated part, expanded and made lighter, ascends, and cooler air flows in from the side to take its place.

Convection Currents.—When any heated surface is exposed to and heats the air near it, the warm air rises from the surface and cooler air flows in from the side to take its place. Currents are set up, which are called '*convection*' currents, because they convey the heat from place to place.

An experiment may be made which will illustrate the existence of convection currents in air. If a lamp chimney be placed over a short candle burning on a table (Fig. 7), the products of combustion will accumulate at the lower part of the chimney and, in a short time, will extinguish the candle. If a piece of sheet-tin be cut to the size of the top, so as to divide it into

two parts, when the candle is burning convection currents will establish themselves, and fresh air will be drawn in on one side of the division, the heated air passing out by the other side, thus providing air for the flame. The smoke of a match or pastille will show the directions of these currents.

Fig. 7.—Convection Currents.

The Trade Winds are examples of convection currents in action on a large scale. The heated air rises at the tropics, while cooler air flows in from north and south. A map of the Trade Winds (Fig. 8) will make this clear. One thing must be remembered in considering this map. Points on the equator are moving from west to east faster than any other points on the earth's surface, and any point nearer to

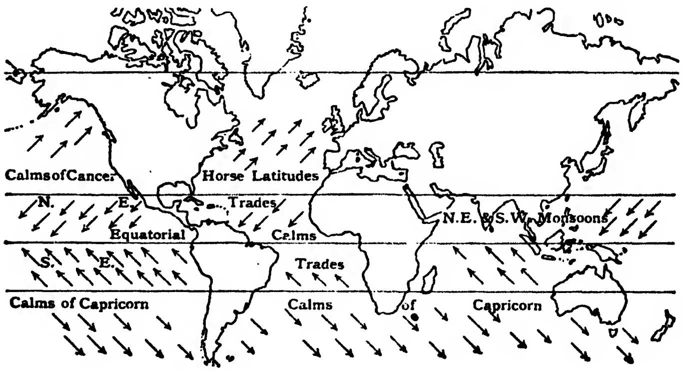


Fig. 8.—Trade Wind systems.

the equator has a more rapid motion eastward than a point farther off. As a consequence air moving towards the equator not having so rapid an easterly motion as the part of the earth it is crossing seems to have a westward movement.

It often happens that a fast express from Bristol to London catches up and passes a local train also going east. As there are

four lines, two for fast and two for slow traffic, between Didcot and London, these two eastward bound trains run quite close to one another. To a person in the fast train the slow train seems to move westward, and in the same way to a person on the faster moving portion of the earth, the air with a slower eastward movement seems to move from the east.

Hence, owing to the earth's movement, the prevailing winds have a westward tendency, becoming north-easterly Trade Winds, which prevail over a zone on the north of the equator, and south-easterly Trade Winds south of the equator. The connection between the Trade Winds and the heating action of the sun is made more evident by the fact that the zones of the Trade Winds move northward and southward with the sun at the different seasons. There is a belt of calm at the equator where the air coming in from both sides is rising. There is also a belt of calm and baffling winds to the north and south of the Trade Wind belts. In this region the higher layers of air which rose at the equator have been cooled below the rest and descend; from that belt northward and southward to the Poles there is a region of variable winds chiefly westerly.

This is the general system of prevailing winds over the ocean, but the action of the sun on large tracts of land heats large bodies of air and causes local currents.

Land and Sea Breezes are caused by the land being heated powerfully by the sun's rays traversing the clear dry morning air. The layers of air near the earth are expanded, raising the layers above them; these flow off seawards, and cause an increased pressure some distance from the land. This gives rise to a stiff breeze, which seems to rise in the offing and progress landwards, increasing till noon, when it sometimes has the force of a gale.

At sunset the opposite occurs, the land cools and the sea remains at the same temperature. This often takes place very suddenly, owing to the rapidity with which the earth radiates heat into space; strong puffs of wind or squally gusts start from the land and blow out over the sea.

Monsoons are attributed by Dove to the same cause. The extreme heat in summer and cold in winter prevailing over the expanse of Central Asia cause periodical winds called the south-westerly or rainy monsoon in summer, and the north-easterly or dry monsoon in winter. These winds prevail in the Indian and China Seas, and this explanation is a plausible one; it is not however accepted by later writers, who mostly consider them to be extensions of Trade Wind systems.

Ventilation. — Ventilation is carried out by the rising of heated air, cooler and heavier air flowing in to take its place. In a room in which men or animals live, ventilation must be provided, by leaving a chimney open even if there be no fire, by

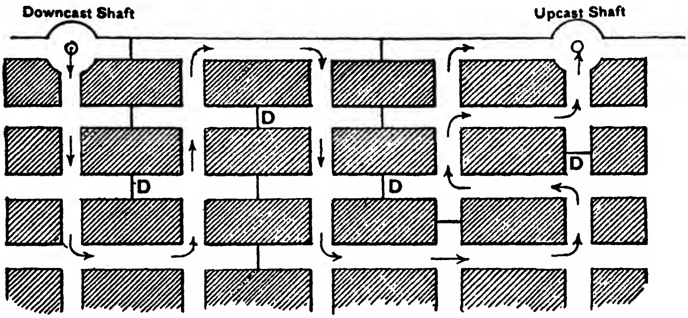


Fig. 9.—Ventilation of mine.

leaving the top of a window open, or in some way allowing heated air to escape. Provision must be made for fresh air to enter, preferably by tubes communicating with the open air and led some way up the wall to avoid the cool air being unpleasantly felt as it comes in. Well-contrived ventilation is necessary in a coal mine. Two shafts are generally provided communicating with the workings. A fire is kept burning at the bottom of one of these; the heated air rises, and a supply of air is drawn through the galleries and down the other shaft (Fig. 9). Doors are placed to direct the current and make it pass wherever men are working. Boys are stationed to open and shut the doors when the 'trammers' pass with the trucks of coal.

In the figure the shafts, workings and doors, some of which are marked D, are roughly shown in plan, to illustrate the ventilation of the pit. In old mines, where there is only one shaft, it is divided by a brattice into two parts, of which one is used for the downcast and one for the upcast or 'smoky' shaft, in which the current is stimulated by a fan.

Refrigerator Engines.—If gas be allowed to expand against pressure its temperature is lowered. This principle is used in the refrigerators generally fitted in steamships constructed to carry meat or perishable cargoes. Air is compressed by powerful pumps and becomes heated. It is then cooled by pipes kept cool by cold water. When allowed to expand into the refrigerating chamber its temperature is lowered. Such an arrangement is shown in plan in Fig. 10.

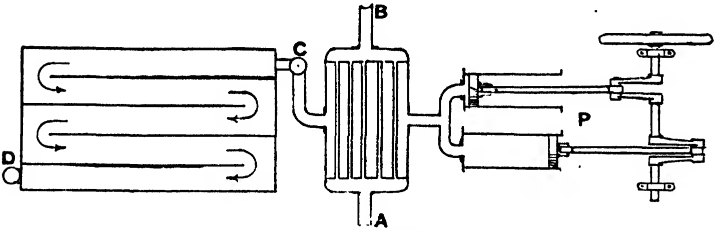


Fig. 10.—Refrigerator engines.

Compressing pumps P compress the air which passes through a cooling chamber kept cool by the circulation of water from A to B. The air thus cooled escapes by a reducing valve C into the refrigerating chamber, and after passing through the chamber escapes into the open air through the valve at D. By means of chambers so cooled, fruit and fresh meat may be kept for months and carried even through the tropics without loss.

Liquid Air is made in large quantities by a similar process. Air compressed at a pressure of some two hundred atmospheres is led from the reservoir through a coil of pipe placed between two vacuum-jacketed cylinders. The object of the vacuum jacket is to avoid the access of heat to the coil. The air after passing to the bottom of the coil is discharged through a pinhole

aperture and is thus very much cooled. It has no way of escape but upwards over the coil, which, with the compressed air contained, is rapidly cooled. The compressed air thus cooled expands on its exit from the pinhole, is cooled and still further cools the coil. This cooling process goes on progressively until liquid air flows from the pinhole and collects in the outer cylinder at a temperature of $-194°$ C.

CHAPTER III

Effects of Heat—Expansion

Liquids

Liquids Expand when Heated—Relative Expansion—Absolute Expansion—Thermometers—Maximum and Minimum Thermometers—Irregularity in Liquid Expansion—Liquids for Thermometers—Anomalous Behaviour of Water—Maximum Density of Water—Hope's Experiment—Consequences of the Anomaly of Water Expansion—Convection Currents—The Gulf Stream—Heating Apparatus.

Liquids Expand when Heated.—"When a specific gravity bottle has been filled and wiped; if it be then held in the hand, the liquid in it is warmed, and expanding oozes through the stopper" (HYDROSTATICS, p. 209). This shows that liquids expand or dilate when heated. The apparatus described at the beginning of the last chapter is most useful for experiments on liquid expansion, the bottles being filled with various liquids instead of gases. The drop of mercury in the tubes can be dispensed with, as the liquids rise in the tubes when the trough is heated.

The liquids are seen to expand when heated, but very differently to gases; whereas the gases expand equally for the same rise of temperature, the liquids rise at different rates in the tubes. Alcohol and spirits of turpentine expand nearly ten times as much as mercury or water at 60° (15° C.). One of the bottles being 'empty,' that is, full of air, acts as an air thermometer, and by it the rise of temperature can be noted. If the expansion of

water relatively to the rise of temperature be noticed, it will be seen that at 86° F. (30° C.) water expands four times as much for a given rise as at 50° F. (10° C.). Such experiments show not only that different liquids have different coefficients of expansion, but that the same liquid has different coefficients of expansion at different temperatures.

Relative Expansion.—Liquids must be contained in some solid vessel, and as this also expands when heated the expansion observed in the foregoing experiment is not the whole expansion of the liquid.

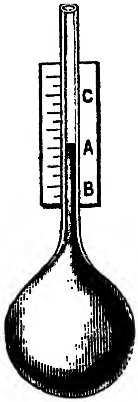


Fig. 11.
Relative expansion.

Take a large bulb, diameter 3 in. (7 cm.), blown on the end of a fine tube. Fill it with coloured liquid so that at 60° F. (15° C.) the liquid stands at A (Fig. 11), half way up the tube. When the bulb is plunged into hot water, the liquid descends to B for an instant and then ascends to C. This is due to the fact that the glass bulb is the first to be heated and expand, allowing more room for the liquid, which therefore seems to shrink. Subsequently the liquid is heated, and as it has a greater coefficient of expansion than that of glass, its expansion is seen by the rising of the liquid in the tube.

Absolute Expansion.—To ascertain the coefficient of expansion of a liquid, the effect of the expansion of the containing vessel must be avoided altogether. This is done by observing the change in the density of the liquid as it is heated; the method of communicating tubes (HYDROSTATICS, p. 191) is used for this purpose.

Two vertical tubes, jacketed with water or oil, are joined by a small horizontal tube at their base. The tubes are filled with the liquid whose coefficient is to be determined; one of them is kept at a given temperature and used as standard, the other can be heated as desired.

The vertical heights of the liquid columns above the horizontal tube are accurately observed, and the temperature of the

liquid is read by an air thermometer. From a series of such observations, the density of the liquid at various temperatures is compared with that of the same liquid at a fixed temperature, and the coefficient of expansion or dilatation of the liquid is found. As a contrast to 'relative expansion,' this, which is independent of the expansion of the container, is called *Absolute Expansion.*

Thermometers.—The expansion of liquids when heated is used for making instruments to measure temperature. It is true that the air thermometer gives an accurate reading of temperature over a great range; but its form is not convenient for practical use. Ordinary thermometers are usually filled either with mercury or alcohol.

THE MERCURIAL AND THE SPIRIT THERMOMETER.—A fine glass tube is provided with a spherical or cylindrical bulb at one end. This bulb and part of the tube are filled with mercury or alcohol, the air being driven out and the end sealed. The expansion of the liquid indicates the temperature by means of a scale.

To construct a thermometer.—Choose a tube with even bore and with a suitable bulb. The open end should have a funnel into which liquid can be poured (see Fig. 12, in which the bore is exaggerated so that it can be plainly seen). (i.) The mercury or the spirit is poured into the funnel. (ii.) The bulb is warmed over a spirit lamp, the air expands, and some of it escapes through the liquid. (iii.) When the bulb cools, the pressure of the external air forces some liquid into the tube and bulb. (iv.) The liquid in the bulb is boiled, and the vapour carries most of the air out. (v.) When the bulb cools, the vapour is condensed, and more of the liquid is forced into the tube and bulb. (vi.) This is repeated, till all the air has been expelled, and the bulb and tube are full of liquid. (vii.) The whole is then heated to the highest temperature which the instrument is required to register; the tube is sealed and the elongation removed. The thermometer tube is now complete.

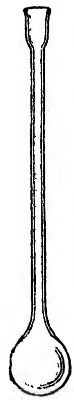


Fig. 12. Thermometer tube.

To graduate the thermometer.—(viii.) Place in melting ice, and when the tube and bulb are at the temperature of the freezing point, mark the position of the liquid on the tube with a file. (ix.) Place the mercurial thermometer in a current of steam from boiling water and mark the tube at the point reached by the liquid. (x.) Divide the distance between the freezing and boiling points into 100 parts for degrees Centigrade or into 180 for degrees Fahrenheit, and continue above or below as necessary.

The spirit thermometer is usually graduated by comparison with a mercurial thermometer. All thermometers should have an enlargement at the upper end, as a safeguard. It may happen that the thermometer is exposed to a temperature above that contemplated in (vii.). The liquid expands, fills the tube, and flows over into this reservoir; if it were not provided, the expansion would break the bulb.

Maximum and Minimum Thermometers—RUTHERFORD'S.—It is sometimes desirable to know the highest and lowest readings of the thermometer during a certain period, *e.g.* the lowest in the night and the highest during the day.

The maximum thermometer is filled with mercury and the tube contains a glass index which the mercury does not 'wet' and cling to. Consequently the index is pushed forward to the furthest point reached by the mercury, and left there when the mercury recedes again.

The minimum thermometer is filled with alcohol, in which the glass index is immersed. The 'surface tension' (p. 125) acts like a skin and pulls the index back to the lowest point reached by the spirit, and leaves it there when the thermometer rises.

The column and index are exaggerated in the illustration (Fig. 13), so that they can be more plainly seen.

Both thermometers can be mounted on the same board, as shown; then they can be 'set' by inclining the whole to the left, for when each index rests on the surface of the liquid they are both ready to register the extremes of temperature.

SIXE'S THERMOMETER.—A combination of maximum and minimum thermometers is arranged, as shown in Fig. 14. A is

the apex of a long bulb which is filled with spirit, so that AB is a minimum thermometer with its index at B. The portion BCD

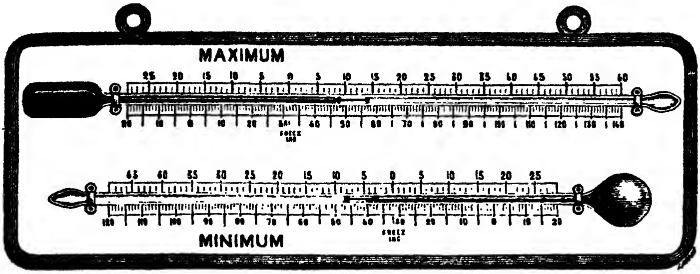


Fig. 13.—Maximum and minimum thermometers.

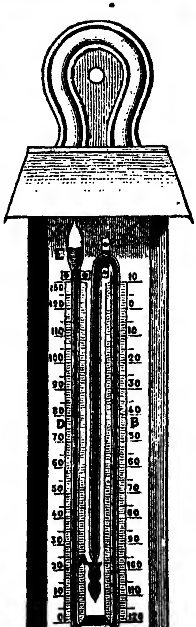


Fig. 14.—Sixe's thermometer.

is filled with mercury, while DE and half the bulb E are filled with spirit in which is immersed a glass index at D. The weight of the liquid DE helps to keep the mercury and spirit in contact at B and ensure correct readings. The reservoir at E is free from air and contains vapour of spirit, it allows room for the expansion of the liquids. Each index has a fine steel spring, which holds it in the tube where it is left by the mercury, but not too firmly to be moved by a magnet.

When the temperature rises, the combined expansion of the spirit AB and mercury BCD forces the index at D forward, and leaves it at the farthest point it has reached. The index D therefore gives a maximum reading. When the liquids contract on a fall of temperature, the weight of the liquid at E forces the mercury column back, keeping the whole column of liquids unbroken. The index at B is thus driven back to the farthest point reached by the spirit AB as it contracts. The reading of the index at B is therefore a minimum reading. The action of the column of liquid DE must be borne

in mind, as the reading of the index D will be too high if the liquids are not in contact at B. A magnet must be used to bring both indices down on to the mercury surface when the thermometer is set.

Maximum thermometers are frequently constructed to record without an index. If part of the fine tube of the thermometer be drawn to extreme fineness, the mercury passes this constriction as it expands; but when it contracts its cohesion is not sufficient to overcome the friction. The column breaks at that point, and the part in the tube remains as an index of the highest reading reached. The thermometer is set by jerking it, when the mercury by its inertia overcomes the friction and passes the narrowed part.

This form is adopted in the CLINICAL THERMOMETER (Fig. 15), used to read the temperature of patients. The column is shown broken at A, below the constriction. The mercury

Fig. 15.—Clinical thermometer.

remains in the tube as an index that the temperature of the patient was 102·9° F.; the rest of the mercury has retreated towards the bulb.

Irregularity of Liquid Expansion.—The rough experiments described at the beginning of the chapter are sufficiently accurate to show that water does not dilate uniformly. When the coefficients of expansion of liquids are accurately determined for equal intervals of the air thermometer, it is seen that liquids do not expand in proportion to rise of temperature. It is necessary to name the temperature at which the coefficient of expansion of a liquid has a certain value, for at another temperature it has a different value. For example, the coefficient of expansion of mercury is ·00179 for each degree C. at 0° C. and ·00183 at 100° C. This change is very small, so mercury may be treated as expanding uniformly between those limits. The coefficient of expansion of alcohol is ·0105 C. at 0° C. and ·0112

at 20° C. For ordinary purposes this may be considered uniform; if accuracy is desirable the alcohol thermometer should not be graduated by equal division but by comparison with the air or mercury thermometer.

Liquids for Thermometers.—Alcohol and mercury are suitable for use in thermometers; (i.) because their expansion is approximately uniform at ordinary temperatures; (ii.) because they can be easily procured pure, and clean mercury does not wet glass; (iii.) because alcohol freezes at a very low temperature and mercury boils at a very high temperature.

Anomalous Behaviour of Water.—The expansion of water when heated is so irregular, and water is so universally present that the expansion of water deserves separate notice. When water at freezing point is heated it contracts until it reaches 39° F. (4° C.), it then expands, and the coefficient of expansion increases as the temperature rises.

The accompanying diagram (Fig. 16) shows the behaviour of water graphically. The upper part shows the changes in length of a column of water 6 ft. long between 0° and 100° C., the actual volume of one gramme of water at any temperature may be read off accurately by the use of the diagonal scale. The changes in the coefficient of expansion are graphically shown. Between 10° and 20° C. the change of volume is ·0015, and between 90° and 100° C. the change is ·0075 of the unit volume.

In the lower part the anomalous behaviour of water near to the freezing point is shown. In this case 1 gramme of water is supposed to fill a tube 200 yards long, when the column would change in length as shown. These diagrams are given instead of a tabular statement. The volume of water at any temperature F. or C. can be accurately read off by means of the diagonal scales.

Maximum Density of Water.—The temperature on either side of which water expands is about 39° F. (4° C., accurately 3·982 C., *Mendeléef.*) At this point a given mass of water has the least volume and a given volume of water has the greatest

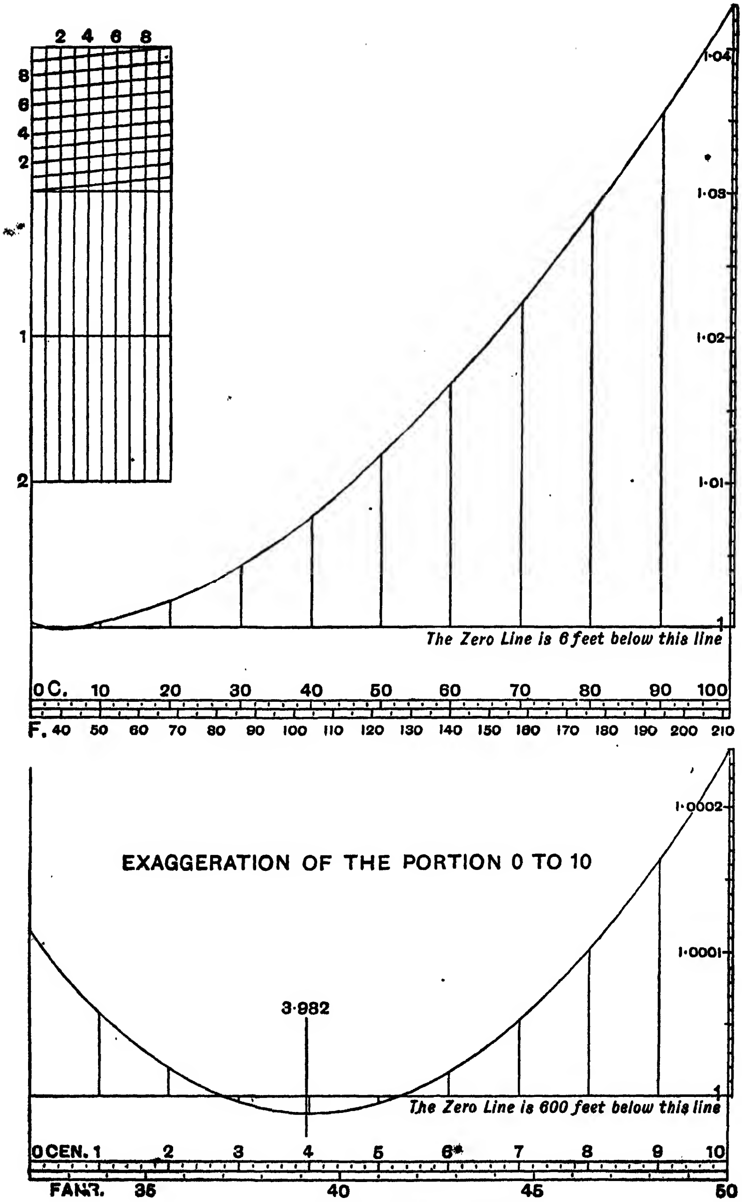


Fig. 16.—Anomalous behaviour of water.

mass; it is therefore called the point of *Maximum Density of water.*

If a very large bulb opening into a glass tube be filled with water, cooled to freezing point, and then be allowed to reach the temperature of the room (about 60° F.), the water in the tube falls, showing that the water contracts, till a thermometer in the bulb shows 39° F. (4° C.). As the temperature rises above the point of maximum density the column rises again. If the glass of the bulb is very thin, the whole of the water in the bulb and

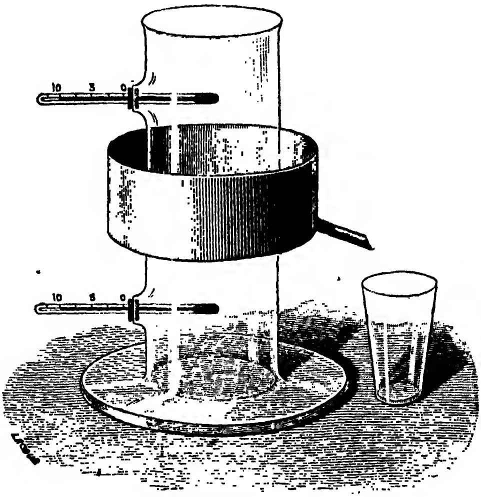


Fig. 17.—Hope's experiment.

the glass together very slowly reach the temperature of the room; and the glass is never much warmer than the water. In this way the effect of the expansion of the glass described on p. 278 is avoided.

Hope's Experiment—*To show the temperature of water at its maximum density.*—A cylinder of metal or glass about a foot high and 4 in. diameter is surrounded by a jacket about its middle part, which will hold ice, from which the water is drained off as it melts (Fig. 17). Thermometers pass through corks, fitted into short tubes above and below the jacket. These

thermometers are graduated on the stem between – 5° and 15° C., and when the bulbs are in the middle of the cylinder all the graduations are outside.

At the beginning of the experiments the cylinder should be full of water, and the whole be at a temperature of about 10° C. (50° F.). A mixture of ice and salt is put in the jacket, and as the water begins to cool the readings of both thermometers should be continuously noted. As the water is cooled by the ice jacket it sinks; warmer water rises from the bottom, is cooled and sinks in turn, so that the lower thermometer shows a gradual fall of temperature, the upper one remaining stationary. The water contracts and becomes denser when cooled, sinking to the bottom of the vessel in consequence.

At a temperature of 4° C. the lower thermometer ceases to fall, showing that the further cooling of the water by the ice jacket does not make it denser. On the other hand, the water in the middle being cooled below 4° C. expands, becomes lighter and rises. Denser water on the top flows down, and the whole of the water above the jacket is cooled. The upper thermometer now begins to fall, continuing to do so until it reaches 0° C.; ice forms in the middle and floats to the top, the lower thermometer remaining at 4° C. This experiment shows that water at 4° C. (39° F.) is denser than at any other temperature higher or lower.

Consequences of the Anomaly in Expansion of Water

What is seen in the tall cylinder of Hope's experiment occurs also in lakes and rivers when it is very cold; only of course in their case the water is cooled from above. The upper layers of water cooled by the air and wind sink and cool the whole to a temperature of 4° C. Below this point however the lower water is not cooled, as the upper water then becomes lighter when it loses heat and the ice formed floats on the surface. Cooling of the lower strata must take place through the ice, and as water and ice are bad conductors of heat, and since as above no convection currents are formed, the cooling of the lower part takes

place very slowly. Fish can continue to live at the bottom after the pond is frozen, and it is rarely the case that a deep pond is frozen solid to the bottom and all life destroyed. No other liquid but water shows this anomaly to any appreciable extent.

Consequences of the Expansion of Water when Heated

If part of a large volume of water is heated (and so expanded and made lighter) it ascends, while cooler water flows in to take its place. In Hope's experiment the reverse of this occurs, as the water is cooled by the ice jacket and sinks until the point of maximum density is reached, when the cooler water rises.

Convection Currents.—When heat is applied to a vessel of water the heated water rises and cooler water flows in to take its place. Currents are set up called 'convection currents,' because they convey the heat from place to place. Such currents can easily be shown.

A glass beaker is filled with water to which ammonia and copper sulphate are added. A white flocculent substance is seen in blue water, and any movement of the water is shown by moving white flakes. A spirit lamp is lighted under the beaker, and the lower part of the water is heated (Fig. 18). The experiment shows the water rising in the middle from the surface of the heated glass, while cooler water flows down the sides to replace the water which rises. Thus convection currents are set up which can be plainly seen.

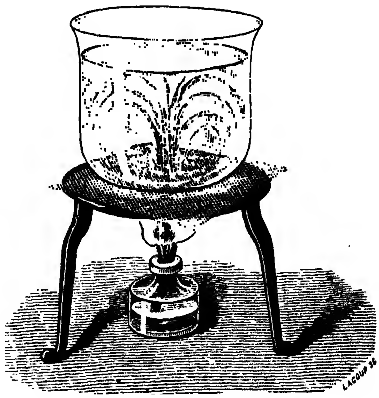


Fig. 18.—Convection currents.

The Gulf Stream is an immense convection current. The

water in the Gulf of Mexico is strongly heated by the sun, and being lighter it flows off northward to make room for the cooler and denser water from the north. This ocean river flows over to the coasts of Britain, bringing evidences of its origin in jetsam of tropical seeds and branches on the coast of Ireland. Its power of 'convection' or carrying heat is shown in the temperate climate and dampness of the British Isles, which are so much warmer in winter than American or even European places in the same latitude.

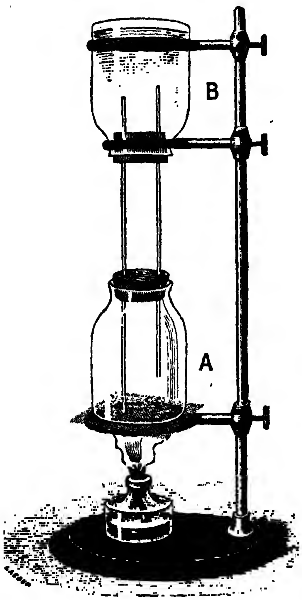


Fig. 19.—Circulation of water.

Heating Apparatus depends on the expansion of heated water, and may be illustrated by the lecture-room apparatus shown in Fig. 19. Take two equal flasks, both stopped by a cork with two holes, and remove the bottom of B. Insert two equal tubes in the cork of A, and let them also go through the cork of B, which is inverted. The tubes being of the same length, one goes to the bottom of A and just through the cork of B, and the other, only going through the cork of A, rises higher in B. A very little sawdust or fine bran is put in the water to show its movement, and a spirit lamp is lighted under A. The heated water is seen to rise by the higher tube and cooler water descends the lower.

The hot water supply of houses is arranged in a similar manner. A closed boiler in the kitchen stove, represented by A, is connected by an upcast and downcast pipe with a tank above, represented by B; the water circulates through the pipes, and there is hot water in the house where required.

On their way between the boiler and the hot water cistern the pipes may be used for heating or drying clothes as desired.

CHAPTER IV

Effects of Heat—Expansion

Solids

Experiments Illustrating Expansion—Linear Coefficient of Expansion—Linear and Cubical Expansion Compared—Linear and Superficial Expansion—Determination of Linear Coefficient of Expansion—Coefficient of Linear Expansion—Practical Consequences of Expansion—Application of the Differences in Expansion of Metals—Compensated Pendulum—Compensated Balance—Pyrometry.

Solids do not expand so much as liquids or gases when heated, yet their expansion is a more familiar fact, because they have linear dimensions—length, breadth, and thickness, which can be easily measured and their values at different temperatures compared.

Experiments Illustrating Expansion

Bar and Gauge.—A rod of metal about a foot long provided with a handle (Fig. 20) fits exactly into a gauge when cool; but when it is heated it is longer and cannot be placed between the ends of the gauge.

Breaking of Bar by Cooling Rod.—An iron rod lies in the notches of an iron frame, and a cast-iron bolt can be passed through a hole at the nearer end of it (Fig. 21). The rod is heated in the fire to a dull red heat and laid in the notches. A bolt is put through the hole and the screw at the end of the rod is tightened, so that the bolt is brought against the V-shaped edges

at the end of the frame. Cold water is poured on the rod, and it shrinks, bringing so great a force to bear on the middle of the cast-iron bolt as to break it.

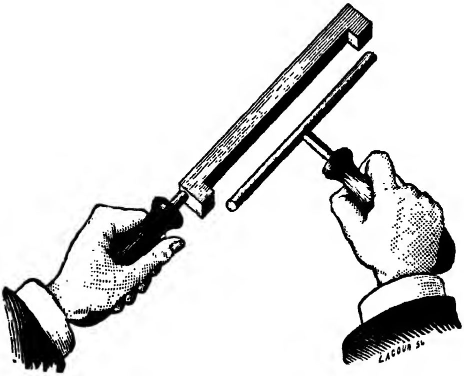


Fig. 20.—Rod and gauge.

Gravesande's Ring.—A hollow sphere of brass, accurately turned, passes easily through a ring when cool (Fig. 22). Having been heated over a spirit lamp the ball rests on the ring and does not fall through until it cools and contracts sufficiently.

These experiments show that solids expand when heated and contract when cooled, as do liquids and

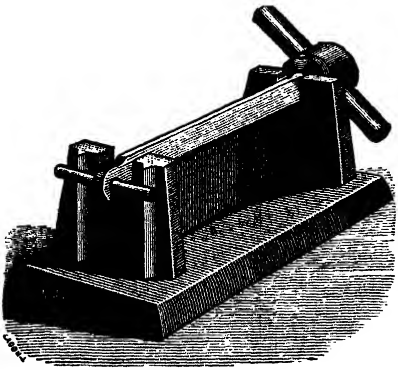


Fig. 21.—Cooling tie-rod.

Composite Strip of Metal.—A thin, flat strip of brass is riveted to a strip of steel of the same size, forming thus a 'composite strip.' This is placed so that its ends rest on two supports, and a spirit lamp is placed so as to heat it in the middle. The composite strip is seen to bend into

the arc of a circle as it is heated, the brass forming the outer part of the arc. This shows that, when heated, brass expands more than steel.

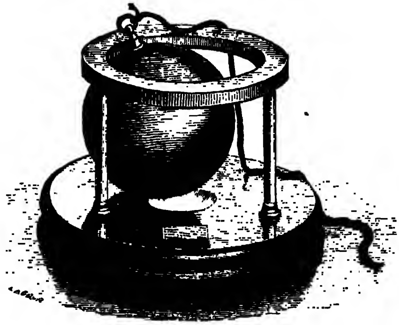


Fig. 22.—Gravesande's ring.

Rod and Index.—Rods of different substances are provided about the same length, so that they can rest in two notches and be heated by the spirit lamps (Fig. 23). An adjusting screw at one end of the rod prevents expansion in that direction, and keeps the other end against the short arm of a lever. Any expansion of the rod must move the lever and cause the index to rise.

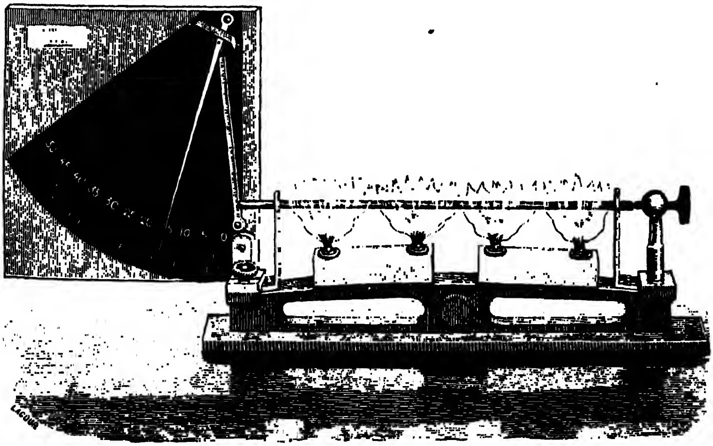


Fig. 23.—Rod and index.

At the beginning of the experiment the rod is placed in the notches cool and adjusted by the screw so as to press against the lever with the index at zero. The spirit lamps are lighted and the rod is heated to the temperature of the flame, the

expansion of the rod being shown by the index. A rod of another material is placed in the notches and heated in the same way.

The number of the graduations read by the index when it comes to rest shows the expansion of the material of the rod in each case, when it is raised to the temperature of the flame. This is seen to differ considerably with different materials; the experiment thus shows that different solid substances have different coefficients of expansion.

With fluids, dilatation, or expansion in volume, alone can be measured; in solids the linear and superficial dimensions can be measured, and as they increase when the solid is heated there are linear and superficial coefficients of expansion.

Linear Coefficient of Expansion.—The linear dimensions of a solid increase for each rise of 1° in temperature by a constant fraction of the original dimension. This fraction is called the *Linear Coefficient of Expansion.*

Linear and Cubical Expansion Compared.—Suppose that a sphere of radius AB expands till the radius is AC. Its increase in volume is a spherical shell of thickness BC (Fig. 24). The volume of the sphere of radius AB is $\frac{4}{3}\pi AB^3$. If a be the linear coefficient of expansion of the material and t the number of degrees through which its temperature has been raised, $AC = AB + AB \,.\, a \,.\, t$. The shell is the difference of the two spheres $\frac{4}{3}\pi AB^3$ and $\frac{4}{3}\pi AB^3(1 + a \,.\, t)^3$. This difference is approximately $\frac{4}{3}\pi AB^3 \,.\, 3at$ (since a is very small $3a^2t^2$ and a^3t^3 are inappreciable). The sphere $\frac{4}{3}\pi AB^3$ has been increased by a spherical shell of volume $\frac{4}{3}\pi AB^3 \times 3at$, so that $3a$ is the coefficient of cubical expansion.

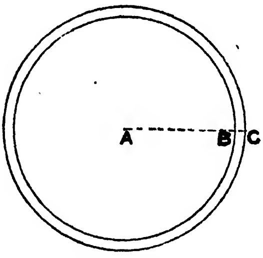


Fig. 24.
Linear and cubical expansion.

The coefficient of cubical expansion is three times the coefficient of linear expansion.

Linear and Superficial Expansion Compared.—Suppose that

a circle of radius AB expands till the radius is AC. The area of the circle is increased from πAB^2 to $\pi AB^2(1 + at)^2$. The increase, *i.e.* the circular ring, which is the difference between the two circles, is $\pi AB^2 \times 2at$ (since the term a^2t^2 is inappreciable), so that $2a$ is the coefficient of superficial expansion.

The coefficient of superficial expansion is twice the coefficient of linear expansion.

Determination of Linear Coefficient of Expansion.—In Roy and Ramsden's method, a standard bar of metal is placed in melting ice to ensure its being at the freezing point (Fig. 25).

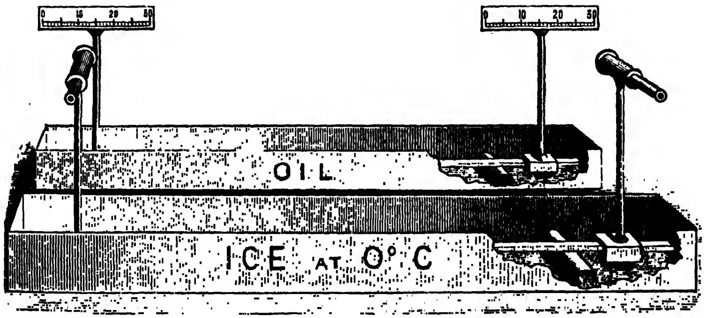


Fig. 25.—Roy and Ramsden's apparatus.

The bar to be experimented on is placed in a bath of oil whose temperature can be varied. The two rods are placed parallel to one another, and rest on rollers, so that they are free to move. The standard bar carries a telescope at each end placed horizontally with axis at right angles to the bar. The experimental rod has also two pillars similar to those which carry the telescopes, and these carry horizontal scales graduated with millimetre divisions. The two zeros being a known number of millimetres apart, the differences in the readings of the scale through the telescopes afford a means of computing the coefficient of linear expansion. For example, the two zeros being 1·312 metre (about 4 ft.) apart, the left telescope reads 6·3 and the right 19·5 when the oil is at a temperature 17° C. Boiling oil is poured into the tray and the temperature when the rod and vessel have had

time to settle is 93° C. The telescope to the left now reads 6·9 and the telescope to the right 18·9, which shows that the bar has expanded 1·2 mm. for a rise of temperature 76° C. The coefficient of expansion is $\frac{1\cdot2}{1312 \times 76} = \cdot000012$.

On account of the smallness of the coefficients of expansion of solids a verbal difference arises in definition of the coefficient of expansion of solids. As solids expand regularly, and by so small a fraction of their dimensions, it is not necessary to state the temperature at which it is the coefficient of expansion, nor the temperature at which the dimension of reference is taken.

COEFFICIENTS OF LINEAR EXPANSION FOR A CHANGE OF 1° IN TEMPERATURE

	C.	F.		C.	F.
Aluminium .	·0000222	·0000123	Pinewood .	·0000050	·0000027
Brass . . .	·0000189	·0000105	Platinum .	·0000086	·0000048
Copper . .	·0000166	·0000092	Slate . . .	·0000104	·0000057
Glass . . .	·0000089	·0000049	Silver . . .	·0000194	·0000107
Gold . . .	·0000141	·0000078	Steel . . .	·0000114	·0000063
Iron . . .	·0000117	·0000065	Tin. . .	·0000209	·0000116
Lead . . .	·0000294	·0000163	Zinc . . .	·0000298	·0000165

A comparison of the coefficients of *cubical* expansion of a solid, liquid and gas—*e.g.* iron, ·0000355; mercury, ·00018; gas, ·00366—shows that the expansion of gas is about ten times that of liquid, and liquid ten times that of solid bodies, the coefficients of different liquids and solids varying very much.

Different qualities of glass have different coefficients of expansion, and glass can be made which has the same coefficient of expansion as platinum. Platinum wire can be inserted in molten glass, and both substances will contract together and leave no interstices when cooling. This important fact is of practical value in the construction of incandescent lamps and other electric appliances.

Practical Consequences of Expansion

The expansion of bodies when heated must be taken into account in the design of metal structures and machinery; while, at the same time, the forces exerted by metals when expanding and contracting are valuable to the engineer and builder, for these forces are very great. The strength of materials is measured by (1) the *tensile strength, i.e.* the force per sq. in. which must be exerted to pull a specimen asunder; and (2) the *crushing strength*, which is the force per sq. in. which a specimen can support without being crushed.

These are the forces which are exerted by materials when contracting and expanding; but it must not be forgotten that both tensile and crushing strength diminish when a metal is heated.

As examples of the employment of the forces of expansion and contraction: *Tyres* are made to fit the wheels and are then heated; thus expanded they slip on easily, and as they cool they contract and are firmly fastened on. *Big Guns* are sometimes built of tubes which are each made slightly smaller than to fit, and then heated and shrunk on. *Riveting* is a very familiar operation to many. Two plates to be fastened together are held whilst a hole is drilled through them both. A rivet is heated to red heat and passed through the hole, and when there is hammered until both ends have heads closely gripping the plates. The contraction of the rivet as it cools grips the plates together with great force.

A most interesting application of the expansion of iron occurred in connection with the completion of the Forth Bridge. "On the 10th October 1889, the lower beams of the connecting girders were coupled up. Artificial heat obtained by burning cotton waste was applied to about 120 ft. of girder in order to obtain the elongation necessary for bringing the rivet holes into position" (*Whitaker's Almanac*, 1890).

As examples of the necessity of taking account of expansion in design: The expansion of iron bridges must always be pro-

vided for. Railway rails on the bridge are not connected firmly with those on the shore. On the Forth Bridge a longitudinal play of 10 in. is allowed for by dovetailing the rails at the joining. Parts of the bridge are on rollers while the bolts to hold the towers on to the piers pass through slotted holes in which the bolts can travel.

In a stove or boiler the firebars must fit loosely, and all parts must be arranged to expand equally. In steam- and hot-water pipes expansion joints are inserted; condenser tubes are fitted in stuffing boxes, so that the tubes may expand freely.

Application of the Differences in Expansion of Metals

The difference in the coefficients of expansion of different metals is made use of in various ways.

Compensated Pendulum.—If a clock has a metal pendulum the expansion of the rod causes the pendulum to swing more slowly in hot weather. It is possible to correct this by a suitable combination of metals.

Harrison's Gridiron Pendulum.—The linear coefficients of expansion of brass and iron are ·0000189 and ·0000117.

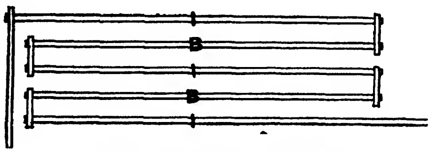


Fig. 26.—Expansion corrected.

The ratio of these coefficients to one another is nearly as 3 to 2. If then two rods of brass and three rods of iron be arranged as shown in Fig. 26, the extreme length is constant at all temperatures, provided the total length of the iron rods I, I, I be to the total length of the brass rods B, B as 189 to 117.

The lowest iron rod is prolonged because twice 189 is greater than three times 117 by 27.

The pendulum thus arranged is shown in Fig. 27. Rods are placed in the order described, but similarly on either side of the central iron rod; the brass rods are darkened.

Mercurial Pendulum.—In this pendulum, frequently fitted to French clocks, the rod is made of iron and the bob consists

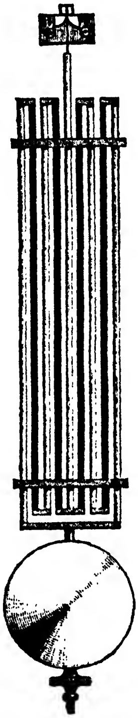


Fig. 27—Gridiron pendulum.

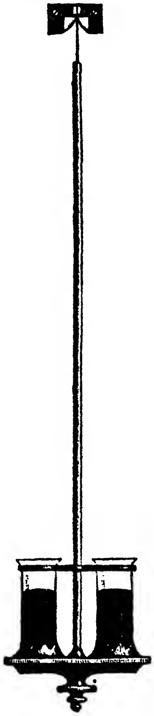


Fig. 28.—Mercurial pendulum.

of two glass cylinders containing mercury (Fig. 28). The coefficient of cubical expansion of mercury is ·00018 and of glass ·0000267; therefore the coefficient of expansion of the mercury in the glass vessels is the difference of these; viz. ·0001533, which is about thirteen times the coefficient of linear expansion of iron, ·0000117.

Hence, if the length of the pendulum be thirteen times the height of the c.g. of the mercury column, the c.g. of the mercury remains at the same distance below the point of suspension, however the temperature may change.

Compensated Balance.—The curvature of a compound strip of brass and steel when heated is used to compensate for the effect of expansion in retarding the oscillation of a balance wheel (Fig. 29). The rim consists of two semicircles, each a composite strip of brass and steel, the brass being the outer strip. When the temperature rises the diameter is increased, and the effect of this is to place the arcs further from the centre; but at the same time the strips become more curved, which brings the free ends nearer the centre. By this means the angular momentum of the wheel is kept unchanged.

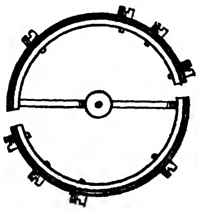


Fig. 29.
Compensated balance.

METALLIC THERMOMETER.—A composite strip of brass and steel is made of a spiral form (Fig. 30), the spiral becomes

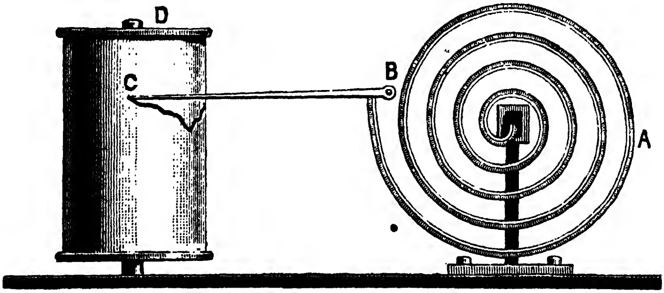


Fig. 30.—Metallic thermometer.

more curved if the temperature rises, and less curved if the temperature falls, provided the outer strip of the spiral be brass and the inner steel. The figure shows the arrangement of such a spiral as a recording thermometer, and the parts are exaggerated and displaced that they may be seen. The end of the spiral A is fixed, and then if the temperature rises

the increase of curvature moves the lever BC and the end C rises, and *vice versâ*. The movement can be recorded on paper fastened to the drum D, which moves by clockwork.

Pyrometry.—The term pyrometry is usually applied to the measurement of temperatures which are beyond the range of the mercurial thermometer.

Such temperatures can be estimated to a certain extent by the eye. In the case of iron a dull red may be considered to be 525° C. (975° F.); cherry red, 800° C. (1450° F.); orange, 1100° C. (2000° F.); white, 1300° C. (2350° F.); dazzling white, 1500° C. (2700° F.). These estimations are of course extremely rough.

The air thermometer is a very valuable and accurate test of temperature up to the melting point of its materials, and metallic thermometers of composite strips can be used up to the welding temperature of the metals.

The electrical condition of metals varies with the temperature. Platinum is used in the pyrometer of Prof. Callender; this is treated of in ELECTRICITY, p. 794.

In conclusion, the first effect of imparting heat, viz. expansion, provides instruments with which temperature may be measured, and further investigations can be conducted with their aid, so that we are made independent of the deceptive answers of our senses.

CHAPTER V

CALORIMETRY

Amount of Heat—Unit of Heat or Thermal Unit—British Thermal Unit—Calorie—Specific Heat—Capacity for Heat—Calorimetry—Calorimeter—Water Equivalent—Favre and Silbermann's Calorimeter.

Amount of Heat.—With the aid of the thermometers which have been described the temperature of bodies can be accurately measured. This being so, the way is cleared for the consideration of the next subject—the amount of heat which a body can impart or receive.

If there be cold water in a basin and hot water be poured into it, the mixture is warm; the more hot water is poured in the warmer the mixture, also the hotter the water, the amount added being the same, the hotter is the water in the basin.

If it be required to keep a tea-urn hot for a school feast in the open air, it is usual to heat an iron bar and to place it in a tube provided for the purpose in the urn. Here, again, a bigger bar will keep the tea hot longer, because it can impart more heat; also the hotter the bar the more heat it can give.

These simple examples illustrate what was said at the very beginning, that the amount of heat which can flow from one body to another depends on the mass of the bodies as well as on the difference of their temperatures. It depends not only on the mass of the hotter body but also on the mass of the colder, for a small body is soon raised to the temperature of a larger one, and then no further heat will flow.

Continuing the illustration of p. 260, if two reservoirs be at the same level and connected by a pipe no water flows, though one be a tea-cup and the other the ocean. But if they are at different levels, the quantity of water that flows depends not only on the amount of water in the higher but also on the capacity of the lower vessel.

The amount or quantity of heat which passes from one body to another must be measured in units, as is the case with any other quantity. Water is the most convenient standard substance in which to establish a unit.

The Unit of Heat, Thermal Unit, or Unit Quantity of Heat is that amount of heat which can raise one unit mass of water at the standard temperature through one degree.

The British Thermal Unit is that amount of heat which can raise 1 lb. of water through one degree Fahrenheit (from 60° F. to 61° F.).

The Calorie is that amount of heat which can raise one gramme of water through one degree Centigrade (from 4° C. to 5° C.).

A kilogramme-centigrade (k.c.) unit and *pound-centigrade* (lb.c.) unit are also used.

The reason for mentioning a 'standard temperature' or a definite rise of temperature is that it takes a little more heat to raise a unit mass of water through one degree at a higher temperature, say from 90° C. to 91° C., than it does from 4° C. to 5° C. (see p. 306). There is, however, no agreement about the standard temperature, and such accuracy is mostly unnecessary in the thermal unit.

Specific Heat.—Two substances, iron and water, have been mentioned in our experiments; so far no measurements have been made, and consequently nothing has been said as to whether iron heats water to the same extent as other water does.

Take 2 lbs. of water and a 2-lb. iron weight for the purpose of comparison, and to ensure them both being at the same temperature, put the iron into the water and boil it over a fire or lamp.

Now provide two separate vessels, each containing 2 lbs. of water at 60° F., and take precautions that they may not lose heat during the experiment by placing them on cork or surrounding with cotton-wool, though the experiment is not intended to be accurate. Pour the boiling water into one vessel, making 4 lbs. in all, and put the 2-lb. weight into the other. The temperature of the 4 lbs. of water is about 136° F.; the 2 lbs. of hot water has lost 76° F. in raising the cold 2 lbs. through 76°.

Allowing time for the iron to reach the temperature of the water, this is found to be about 75° F.; the 2 lbs. of iron has lost 137° in raising the 2 lbs. of water through 15°.

It is evident from this that water differs from iron as to the amount of heat required to raise its temperature through a certain range. From the rough experiment it appears that the amount of heat requisite to raise 2 lbs. of water through 15° is provided by 2 lbs. of iron cooled through nine times that range. Reasoning from this, a British thermal unit which can raise 1 lb. of water through 1° F. could raise about 9 lbs. of iron through 1° F., or the amount of heat requisite to raise 1 lb. of iron through 1° F. is $\frac{1}{9}$ of a British thermal unit. This last conclusion suggests the mode of defining specific heat.

The Specific Heat of a substance is the number of thermal units necessary to raise a unit mass of the substance through one degree.

The Capacity for Heat of a body is the number of thermal units necessary to heat the body through one degree.

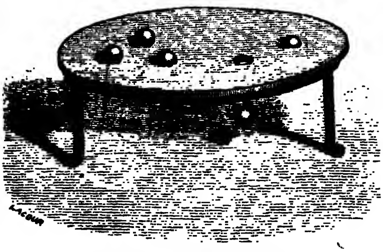


Fig. 31.—Specific heat.

The following experiment also shows how bodies differ as to their specific heats.

A flat circular plate of bee's wax or solid paraffin about $\frac{1}{2}$ in. thick is supported horizontally on a frame (Fig. 31). Balls of various materials—iron, brass, copper,

tin, lead, glass, and stone of about the same weight, that is of the same mass, are heated to the same temperature in a bath of boiling oil.

The balls are taken out of the oil and placed at once on the plate, and they melt their way through the plate very differently. Though all at the same temperature they vary very much in the amount of heat they can give out to melt the wax. The copper and the iron balls melt their way through, and the others penetrate to varying depths.

The balls are at the same temperature and of the same mass, the amount of heat they can give out depends on their specific heat.

Calorimetry.—In observations on quantity of heat care must be taken to avoid any loss of heat during the operations of mixing, etc.; for this purpose a specially designed apparatus is employed.

A Calorimeter is conveniently made of thin copper *polished*, with a cover as C (Fig. 32), and suspended in a similar but larger vessel B. Slate supports F, F keep it in place and allow an air space all round it. The outer vessel B should again be packed in a case A and supported by slate props so that wool may be lightly packed between the two. The outer vessel B can then gain or lose very little heat itself, and the calorimeter C is completely guarded. The stirrer D has a thermometer E in the handle, and both B and C have loosely-fitting covers.

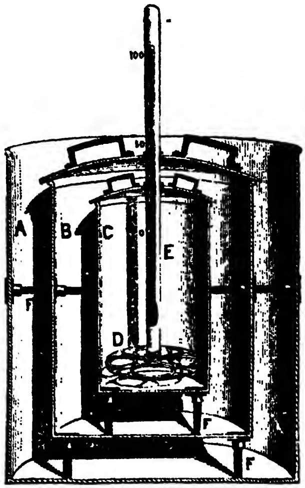


Fig. 32.—Calorimeter.

The water in the calorimeter is stirred so as to be at a uniform temperature throughout, and this is read by means of the thermometer, without the covers being removed.

Besides taking precautions against gain or loss of heat from outside during the experiment, it is necessary to make allowance for heat expended in warming the calorimeter itself or the reverse. It is as though water equivalent in thermal capacity to, and of the temperature of, the calorimeter were added to the mixture.

The Water Equivalent is the capacity for heat of calorimeter and stirrer.

To prove that the amount of heat necessary to raise the temperature of water is proportional to the rise.

Weigh 2 lbs. of water at 98° F. into the calorimeter and add to it 4 lbs of water at 42° F. The water equivalent of the calorimeter is ·6 thermal units, and the temperature of the calorimeter at first 60° F. (The British thermal unit is used in this example.)

The resulting temperature of the water and calorimeter is 60·6° F. 2 lbs. of water at 98° F. with 4 lbs. at 42° and ·6 lbs. at 60° F. contain as much heat as 6·6 lbs. at 60·6° F. The experiment shows by the *method of mixing* that the rise of temperature is proportional to the amount of heat added.

To find the specific heat of solids.—Balls of equal mass but of different materials are heated in a bath of oil and placed in turn in the calorimeter. The specific heat of each ball is ascertained by observing the rise of temperature in the water.

A ball of copper weighing 500 grammes is heated in oil to 120° C. and placed in a calorimeter in which is 1 k. of water at 15° C. The water equivalent of the calorimeter is ·2 k.c. units. The temperature is raised to 19° C. Find the specific heat of copper.

Here, to raise water and calorimeter through 1° C., 1·2 k.c. units are required; to raise them through 4° C., 4·8 units are necessary.

The number of thermal units given out by ·5 k. of copper when cooling through 101° C. is 4·8 k.c. units, therefore the number

of units given out by 1 k. of copper when cooling through 1° C. is

$$\frac{4 \cdot 8}{\cdot 5 \times 101} = \frac{9 \cdot 6}{101} = \cdot 095.$$

Hence the specific heat of copper is ·095.

To find the specific heat of a liquid.—Fill the calorimeter with a known quantity of liquid and conduct the operation in a similar way.

A calorimeter is filled with 1 k. of paraffin oil at 15° C., a ball of iron weighing 500 grammes heated in oil to 120° C. is placed in it. Water equivalent of calorimeter, ·24 k.c. units.

The temperature is raised to 21° C. Find the specific heat of paraffin. (Specific heat of iron, ·113.)

The iron ball has been cooled through 99° C., giving out $\cdot 5 \times 99 \times \cdot 113 = 5 \cdot 59$ k.c. units. To raise the calorimeter through 6° C., 1·44 units are required.

Therefore 4·15 k.c. units are required to raise 1 k. of paraffin through 6° C.

To raise 1 k. of paraffin though 1° C., ·69 unit is required. Hence, the specific heat of paraffin oil is ·69.

SPECIFIC HEAT OF CERTAIN SUBSTANCES

S.H. of Water at 0° C. = 1.

Solids.		Liquids.	
Aluminium	·215	Alcohol	·615
Brass	·0939	Carbon di-sulphide	·221
Copper	·095	Ether	·517
Glass (?)	·192	Glycerine	612
Gold	·0324	Mercury	·0333
Ice	·5	Paraffin (?)	·683
Iron	·113	Turpentine	·467
Lead	·0315		
Platinum	·0324		
Silver	·0559		
Steel	·118		
Tin	·0559		
Zinc	·0935		

The specific heat of water considerably exceeds that of all other substances. Consequently heating is done by water better

than by any other substance, since it gives out more heat for a given loss of temperature; the same is true of cooling.

More heat is required to change the temperature of water through a certain range than any other substance. Consequently the water on the globe is a great equaliser of temperature; water is not heated by the sun so rapidly as land, and

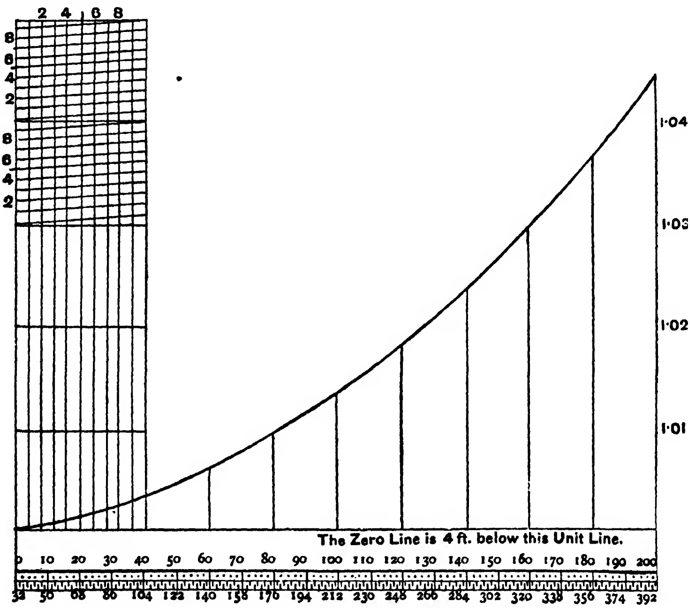


Fig. 33.—Specific heat of water.

it does not lose its heat so soon in the absence of the sun's rays.

The specific heat of liquids is, as a general rule, greater than that of solids; and the specific heat of a substance in the liquid state is greater than that of the same in the solid state, *e.g.* specific heat of ice, ·5.

This is part of the general principle that the specific heat increases with the temperature of the substance. The changes in the specific heat of water are given by the diagram (Fig. 33).

For example, one unit of heat is required to raise one unit-mass of water through 1° at freezing point, while at boiling point 1·013 units, and at 200° C. 1·044 thermal units are required. At the last-mentioned temperature the water is under a pressure of 16 atmospheres. At the freezing point there is a sudden break in the curve, 2 ft. downwards.

The small specific heat of mercury should be noticed. Its utility as the liquid in thermometers depends on this, for it rapidly assumes the temperature of the fluid in which it is placed, and it absorbs but little heat from the fluid in changing its temperature.

Other forms of calorimeter are described when the subject in which they are used is discussed (pp. 311 *sqq.*, 337).

Favre and Silbermann's Calorimeter consists of a mercurial thermometer with a very large bulb of cast-iron. A copper tube in which may be placed specimens of substances whose specific heat is required is inserted in the side of the bulb, so that the substance is almost wholly surrounded by the mercury. The whole bulb is packed in non-conducting material, after a cap has been placed on the tube. Then all the heat given out by the substance in cooling produces an effect in the expansion of the mercury.

To Find the Specific Heat of Gas.—The simple calorimeter described above can be used with a slight modification. A thin copper tube of fine bore and considerable length is formed into a coil which fits into the calorimeter. A known volume of gas at known temperature and pressure is drawn through the tube, and in its passage raises the temperature of the water in the calorimeter. The changes in the temperature of the water and the gas compared with the masses of gas and water give the specific heat of the gas.

The gas in this case is at a constant pressure. The specific heat of gas at constant volume in all cases is about ·71 of the specific heat at constant pressure.

Regnault determined the specific heat of various gases under both conditions. He found that the specific heat of

any gas does not vary with its temperature nor with its pressure.

SPECIFIC HEAT OF SOME GASES

Water = 1.	At constant	
	Pressure.	Volume.
Air	·2375	·1684
Oxygen . . .	·2175	·1551
Nitrogen . .	·2438	·1727
Hydrogen . .	3·409	2·411
Steam . . .	·4805	·37

CHAPTER VI

Effects of Heat—Change of State

Solid to Liquid

The Three States of Matter—Melting—Sensible Heat—Latent Heat of Fusion—Latent Heat of Water—Freezing Mixtures—Table of Melting Point and Specific Heat—Melting Point—Freezing Point—Weakness through Heating—Change of Volume—Melting Point and Pressure—Regelation.

The Three States of Matter.—The fourth and most remarkable effect of imparting heat to a body is to cause it to change its state. It is well to think in general what this means. The ice-floes of the Arctic Regions, that barrier which intrepid spirits are ever trying to pass; the 'countless smile of ocean,' bearing on its bosom the argosies of nations; the invisible vapour, gentle dispenser of health and powerful agent in all progress and discovery—all these are water, but differing as widely as any substances could possibly differ in their states of solid, liquid, and gas. This difference of state is caused by heat.

Most substances are capable of existing in these three states, though water is the only one which comes under ordinary observation in all the three, and is solid, liquid, and gas at temperatures commonly met with. For example, iron is familiar to us only as a solid, but we know that it melts at a high temperature, and that it is present as a gas in the sun. Air is only known as a gas, but modern methods have introduced us to liquid and even to solid air.

The present chapter deals with the change of state from solid to liquid and the reverse. A solid body of definite shape and able to resist stress in any direction is changed by the addition of a certain quantity of heat into a liquid, unable to resist any but a compressive stress, a 'mobile' substance unable to withstand any shearing stress.

The first experiment introduces some very cold ice. In a temperate climate ice is usually looked on as a substance at freezing point. Such is far from being the case in Arctic Regions, or even in Canada or Russia, where the winters are very severe and ice is often many degrees below zero. Even in temperate climates it is not wise to assume that ice is at the freezing point.

Melting.—Take some ice at 20° F., pound it small and place it in a beaker in a basin of hot water. A glass thermometer graduated on the stem should be used to stir the ice. The first effect observed is that the temperature of the pounded ice rises; it does so until the thermometer stands at 32° F., and some of the ice melts. Then if the thermometer continually stir the ice and water, it is seen to remain at the freezing point and no longer to rise. The thermometer remains at 32° F. until all the ice is melted, and then the temperature begins to rise again.

The temperature of a solid at the melting point does not change during fusion.

The basin of hot water loses heat continuously, so that evidently all the heat it has given out has not gone to raise the temperature of the beaker and its contents.

Sensible Heat is heat which changes the temperature of a body.

That heat has been otherwise employed can be seen in the following rough experiment.

Take 1 lb. of ice at 32° F. and place it in a vessel containing 10 lbs. of water at 65° F., taking some precautions to avoid loss or gain of heat from outside. Now if 1 lb. of water at 32° F. had been placed in the vessel instead of the ice, the water in the vessel would have parted with 30 units of its heat, raising

the cold water to 62° F., the water itself being cooled to 62° F.

With the ice, however, it is different; the ice is melted, and the temperature of the water is found to be about 50° F. The ice has disappeared, forming 1 lb. of water, which has been heated through 18° F. The 10 lbs. of water have been cooled from 65° to 50° and 1 lb. of ice has been raised from 32° to 50°, so that about 132 units of heat have disappeared.

Latent Heat of Fusion is the number of units of heat which must be added to a solid to change one unit of mass into liquid without change of temperature.

So long as the corresponding unit of heat is chosen, the unit of mass may be the kilogramme, gramme, or pound without altering the numerical value of the latent heat. The Centigrade and Fahrenheit values are in the ratio 5 : 9.

The latent heat of fusion of ice, called also the Latent Heat of Water, is 79·25 C. and 142·65 F.

Latent Heat of Water.

To Determine the Latent Heat of Fusion of Ice.

i. *The Ice-Block Calorimeter*, devised by Black, who was the first to observe latent heat of fusion.

A block of ice has a cylindrical hole about 2 in. (5 cm.) diameter bored in it; the hole is covered with a slab of ice. A ball of metal which goes easily into the hole is heated to some known temperature, such as that of boiling water. The ice-cavity is carefully dried and the ball dropped into it (Fig. 34). When the ball has been long enough in the hole to reach the freezing point the water which is in the hole is poured out and weighed.

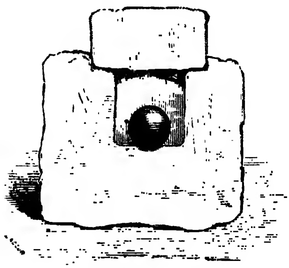


Fig. 34.—Ice block.

An iron ball $1\frac{1}{2}$ in. diameter at a temperature of 100° C. is put into an ice block, and melts one ounce of water. What is the latent heat of water (*Centigrade*)?

An iron ball $1\frac{1}{2}$ in. diam. weighs ·46 lb., and when cooled to

0° C. has parted with $\cdot 46 \times 100 \times \cdot 113 = 5\cdot 2$ lb. c. units of heat, and thus has melted $\frac{1}{16}$ lb. ice.

Therefore $5\cdot 2 \div \frac{1}{16}$ lb. c. units are necessary to melt one pound of ice, and the latent heat of water is 83·2.

The method is a rough one, and the result obtained is only approximate.

ii. *The Calorimeter Method.*—A known quantity of water is placed in the calorimeter (p. 303), the temperature being observed. A piece of ice of known mass is put in it, and the cooling of the water in the calorimeter is observed. In fact the simple experiment with which we began is carried out carefully with apparatus of precision. The comparison of the weight of ice melted and the number of units of heat imparted by the water gives the latent heat.

In a calorimeter containing 1 k. of water at 23° C. is placed 265 grammes of ice at $-3°$ C.; the water equivalent of the calorimeter is ·2 k.c. units. The temperature when all the ice is melted and the water well stirred is 4° C.

The water and calorimeter have been cooled through 19° C.
They have lost in *sensible heat* $1\cdot 2 \times 19 = 22\cdot 8$ k.c. units of heat.
The ice has received ,, ,, $\cdot 265 \times 7 = 1\cdot 8$,, ,,
Disappeared as *latent heat* employed in
melting ·265 k. of ice . . 21 ,, ,,
Therefore $21/\cdot 265 = 79\cdot 25$ = *latent heat of water.*

iii. *Lavoisier and Laplace's Ice Calorimeter* is the same in principle as the ice block. The amount of ice melted by a known mass at a known temperature in cooling to the freezing point is ascertained.

It is used for finding the latent heat of water and also the specific heat of substances, the latent heat of water being known. The body is placed in a thin vessel similar to C in the simple calorimeter (see Fig. 32), but usually smaller. The cover being put on, C is surrounded entirely with ice, so that B is full of ice.

The ice in the vessel B is melted by the heated substance, and the water is run off into a beaker to be weighed. To avoid

any melting of ice in the vessel B through heat from outside, the vessel A is filled with ice, and the cover of it is also heaped with ice. No drain should be provided for the vessel, as the ice and water in it should be at freezing point, and the water ensures that the temperature is not lower than that.

In all cases where it is desirable that ice should be kept cold and melt as little as possible, a drain should be provided. Ice for sick-room use should be kept dry on a cloth stretched over a basin.

But if the object is that the temperature should be that of the freezing point, ice should be left in contact with the water, which will have that temperature.

Freezing Mixtures.—When melting, a solid must absorb heat from its neighbourhood. The addition of sugar cools a cup of tea more than putting in an equal piece of stone, for example. A mixture of pounded ice and salt has a tendency to melt and become brine. To do so it must absorb heat, which becomes 'latent,' and the liquid produced is at the freezing point of brine $-22°$ C. ($-8°$ F.). Such a mixture is called a freezing mixture, because cold may be produced by it, and water or other liquids may be frozen.

The familiar apparatus for producing ices is shown in Fig. 35. The bucket is filled with the freezing mixture, and the cylinder is rolled about in it; the motion causes different parts of the contents of the cylinder to come in contact with the sides as they are cooled by different parts of the mixture in the pail.

Fig. 35.—Ice pail.

It is a common practice, which cannot be too strongly condemned, to sprinkle salt on the pavement and streets after a fall of snow. The snow is melted; but, as has been seen, the slush

produced is intensely cold, and dangerously lowers the temperature of the feet of passers-by, of the ill-shod poor especially, thus endangering the health.

TABLE OF MELTING POINT AND LATENT HEAT OF FUSION OF CERTAIN SUBSTANCES

	Melting Points.		L.H. of Fusion.	
	C.	F.	C.	F.
Air	-210	-346		
Aluminium	657	1214		
Brass	1015	1860		
Carbonic dioxide	-78·2	-108·7		
Copper (in air)	1062	1943		
Gold	1064	1947		
Ice	0	32	79·25	142·65
Iron (pure)	1503	2737	23·	41·40
Lead	327	620	5·37	9·66
Mercury	-39·5	-39·1	2·83	5·09
Platinum	1710	3110	27·18	48·92
Silver (in air)	955	1751	20·07	36·13
Tin	232	449	14·25	25·65
Zinc	419	786	28·13	50·63

Ammonia nitrate crystals in water produce a low temperature, - 15° C. (5° F.). Sulphate of soda with dilute hydrochloric acid or nitrate of potash and salammoniac solution are also available as freezing mixtures; but freezing on a large scale is carried on by other methods, one of which was described on p. 275; others will be described later (p. 342).

Melting Point—Freezing Point.—The temperature of the melting point is the same as that of the freezing point. In the case of water the temperature of the melting point is 0° C. (32° F.), and the experiment described on p. 310 shows that the temperature of a solid at the melting point does not change during fusion. For the basin of hot water substitute a basin of freezing mixture, and fill the beaker with water. The temperature falls to 0° C., and crystals of ice appear; if now the water be stirred with the thermometer, the temperature remains

at 0° C. until the whole of the water is frozen, showing that the freezing point is the same as the melting point.

Weakness through Heating.—The change of state from solid to liquid takes place at a definite temperature for each substance. But many substances, when at a temperature below the melting point, have a lower limit of elasticity and become plastic. For example iron, when heated beyond a dull red heat gradually loses its rigidity and tenacity. The crowns of furnaces and combustion chambers become unduly heated if they are not covered with water, and being weakened, they collapse under the pressure of steam. Iron pillars and girders are often a source of danger in construction; in case of fire they become heated, their crushing and tensile strength are diminished, so that they can no longer support the weight they are designed to bear, and the buildings collapse.

When very near the melting point iron is of the consistency of putty, and two pieces of wrought iron in that condition can be moulded together into one piece. This is called *welding* (see p. 318).

These examples show that, in some substances, fusion and solidification are gradual processes.

Change of Volume at the Melting Point.—Some substances expand while other substances contract when melting, and the reverse when freezing. That water expands when freezing should be well known by every householder, as pipes full of water are split when it freezes, and the thaw when it comes liberates the water. Ice floats on water, and icebergs sometimes tower 50 feet high out of the water; unless the iceberg is aground, there must be nine times as much ice below water as above. (Specific gravity of ice at 0° C., ·918; of sea water at 0°, 1·026).

Water expands about 9 per cent in freezing, and then contracts as cooling proceeds (linear coefficient of expansion ·000052 C.). Fig. 36 shows a continuation of Fig. 16 (Anomalous behaviour of water) to $-10°$ C.; in this there is an instantaneous rise of 27 ft. in the curve at freezing point. There is no perceptible plastic interval in the case of water. The diagram represents the behaviour of a column of water which is

100 yards long—of 1 gramme of water if its volume to the unit line is 1 cub. cm.

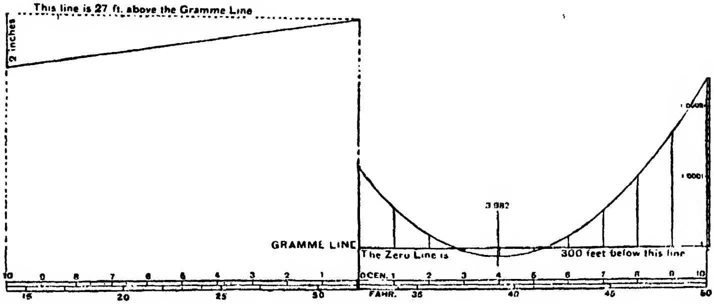


Fig. 36.—Behaviour of water near the freezing point.

Bismuth, lead, and brass expand when solidifying, so that they take the shape of a mould when cooling. When the molten metal is run into a mould the expansion of the solidifying mass forces the metal into every corner of the mould. Silver and gold contract when solidifying; gold and silver coin and medals cannot be cast with so sharp an outline, and they are stamped with dies.

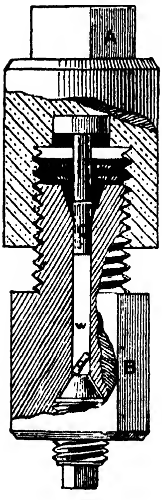


Fig. 37.
Mousson's experiment.

Melting Point and Pressure.—If a body which contracts when it melts is subjected to pressure, it would seem natural that it should melt more easily, that is, at a lower temperature. Conversely a body which expands on melting must be hindered by pressure from melting and melt at a higher temperature.

Mousson's experiment proved this to be so in the case of water. A cylindrical hole *w* is bored in a steel bolt B, which screws into another steel bolt A, both having squared heads. When they are screwed together the copper plug C, which is slightly conical, is forced into *w* (Fig. 37). The whole is inverted, and *w* is filled with water through the

bottom hole, which is closed with a screw plug, after a small steel index o has been introduced, which then rests on C. The apparatus in this position is exposed to a very low temperature in a freezing mixture, so that the index is frozen into the water at what is in the figure the upper end.

The bolts are now inverted to the position shown, and are screwed together with powerful screw wrenches, the whole being kept in a freezing mixture. To avoid warming the apparatus by the mechanical work done on it, this must be done very slowly. Mousson moved the screw A through only 45° at a time, taking four or five minutes to do this, and leaving it four hours to cool between the movements.

When the lower screw-plug was removed a cylinder of ice shot out, the steel index being at the end of it, showing that, in spite of the low temperature, − 18° C., the water had been melted and allowed the index to fall. Mousson estimated the pressure exerted to be about 1300 atmospheres.

Regelation.—If a slab of ice be supported at the ends and two equal weights be hung from the middle of it by a copper wire joining them, the pressure of the wire causes the ice to melt, and the water thus formed freezes above the wire again. Consequently the wire gradually passes down through the ice, and the weights fall without any cut being left in the slab.

If two slabs of ice be pressed together the ice surfaces in contact melt; when the pressure is removed the water thus formed is frozen again and the slabs are united. This freezing again is called *Regelation.*

This is ingeniously used in the Van der Veyde system of ice-making. Pure water is frozen in small cubes, each marked with the trade mark. Several cubes are then frozen together by pressure and sold in blocks. The planes of regelation are not so strong as the rest, and are planes of cleavage. The whole easily breaks up into the cubes, while each bears the stamped guarantee of purity.

The formation and the motion of glaciers is apparently due to melting and regelation. The pressure of the masses of

avalanche snow and ice from above causes the accumulated ice and snow to melt, and then they freeze again into the clear blue glacier ice. Also, as the pressure of the ice masses above causes the glacier to press on the floor and sides of the glacier bed, the ice is melted and yields, freezing again in a new position. As a consequence, a glacier moves down its valley as a viscous liquid, much as pitch would move, though ice is really a solid. The motion of a glacier has been compared to that of a river of mortar flowing down a valley, its middle faster than its sides.

Welding is an example of regelation. Lord Kelvin and his brother, Professor James Thomson, have shown both by theory and experiment that any body which expands when cooled and contracts when heated is cooled instead of heated by pressure.

Cast-iron expands about 7 per cent of its volume at 1300° or 1400° C. as it passes from the solid to the plastic condition, a fact used by Moissan (1906) in making artificial diamonds, and it then contracts about 6 per cent as it melts. Wrought-iron cannot be commercially melted; in the laboratory it has a melting point ranging from about 1500° C. for pure iron to 1400° C. for iron with 1 per cent of carbon. In its plastic condition, say at 1200° C., it contracts when heated, and it is in that state that welding can be done. Two pieces of wrought-iron are brought to a welding temperature; pressure is then applied; the temperature of the joint falls some 50° C. at the junction, owing to the pressure, and the union is effected.

The reason that iron with over 1·5 per cent of carbon and high carbon steel will not weld appears to be that they are mechanical mixtures of substances with different melting points.

CHAPTER VII

Effects of Heat—Change of State

Liquid to Gas

Condensation and Evaporation—Evaporation in Open Air—Dalton's Experiments—Diagram of Pressures—Vapours of various Liquids—Volatile Liquids—Saturated Vapour—Unsaturated Vapour—Adiabatic Expansion—Critical Temperature—Vapours and Gases—Mixture of Gases and Vapours—Voluminometer Method—Dalton's Laws of Vapours.

Condensation and Evaporation.—A tumbler full of very cold water has a most refreshing appearance when it is brought into a hot crowded room; its coolness is proclaimed by the dewy mantle which it wears; the very heat which oppresses us breathes its tokens on the glass. Then, if it remain in the room untouched, its freshness soon fades, the moisture which hung around it vanishes whence it came, and an unattractive glass of water remains.

This is a very simple experiment, and a correct inference from the facts observed in it forms the subject of this chapter.

What is seen to take place is first CONDENSATION when the water, invisible and permeating the air in the state of gas, becomes liquid in what is called 'dew' on the glass; and afterwards EVAPORATION, when the water which was standing in drops on the tumbler disappears, having become water vapour or steam, a gas which is invisible.

If a thermometer be brought into requisition, some of the conditions of these changes of state may be observed. If the

temperature of the room be 72° F. (22° C.), and the water when it comes in be 50° F. (10° C.), the effect is certain to be very marked; the glass will be thickly covered with drops of water. Then as the water in the tumbler becomes warmer, the 'dew' gradually evaporates, and though the tumbler is still much cooler than the room, perhaps at about 61° F. (16° C.), its surface becomes quite free of moisture.

Evaporation and condensation are here seen to take place at a temperature evidently less than 72° F., and the same experiments with iced water and cooled rooms, or even with tepid water and very warm damp rooms, lead to the conclusion that *evaporation and condensation take place at any temperature.*

Evaporation in Open Air.—If water be left in an open dish it evaporates, and the dish becomes dry. The records of observations made during several years show that the evaporation from a free water surface amounts in London to about 20 inches in depth annually, rising to as much as 88 inches at the Equator. Evaporation goes on at the lowest temperatures and ice evaporates without melting.

The conditions of evaporation will be further discussed later on, but it is best here to dispel the prevalent idea that 'boiling' is the change from the liquid to the gaseous state, and that the 'boiling point' is the temperature of transition from the liquid to the gaseous state, just as the 'melting point' is the temperature of transition from the solid to the liquid state. This is not the case; boiling is something quite different from evaporation, and the conditions under which each takes place must be separately considered.

Now if the tumbler of cold water be brought in from outside, it may be noticed that it is free from 'dew' so long as it is in the open air, which is drier than the room. Again, when its surface has become quite dry, if it be taken into a conservatory, where the air is damper than in the room, moisture is again condensed on the glass. It may be arranged that the temperature of the air in all three places may be the same, but anyhow

the experiments show that *the temperature of evaporation depends on the amount of water vapour present.*

The experiments which have been described have served to introduce the main principles of the subject. For more exact discussion of the laws of evaporation more accurate apparatus is required.

Dalton's Experiments.—Two barometer tubes are set up in a cistern of mercury, to which a long handle is attached giving support to the tubes. Thermometers are fastened to the handle at the top and bottom. The whole can then be lowered into a tall glass jar of water, and a stirrer is provided to ensure all the water being at a uniform temperature throughout (Fig. 38). The object of the bath of water is to ensure that the barometer tubes should be at a definite temperature, which is read by the thermometers. The water in the bath may be cooled by means of a jacket of freezing mixture, or warmed by a steam-pipe led into it, so that it may be at any required temperature.

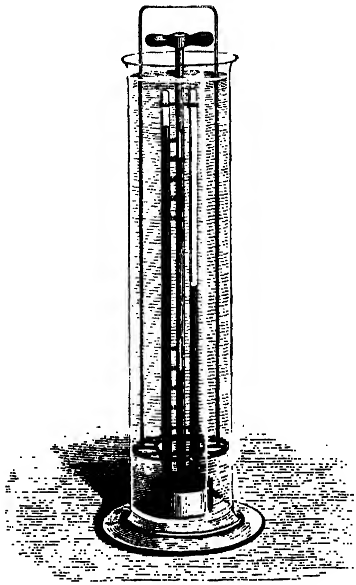


Fig. 38.—Dalton's experiment.

Before the cistern and tubes are lowered into the jar some water is introduced into the right-hand tube by means of a syringe or pipette. It rises to the surface of the mercury and evaporates at once; if sufficient water be introduced, some of it will remain liquid on the surface of the mercury. The water should be previously boiled to ensure its being free of air.

Directly the water is put into the tube the column of mercury

falls, showing that the water vapour exerts pressure, and the amount of this pressure is measured by the distance through which the mercury is depressed below the left-hand column, in which there is no water.

The cistern and tubes are lowered into the bath, and if it is gradually warmed the vapour exerts a greater pressure, and the right-hand column is more and more depressed below the column of reference. This shows that the pressure of water vapour increases with the temperature.

These experiments, which were originally conducted by Dalton, very much in the form shown in Fig. 38, show that so long as there is liquid unevaporated above the mercury the water vapour exerts a certain pressure at each temperature.

If the temperature rises, more liquid is evaporated, and the pressure increases; if the temperature falls, some vapour is condensed, and the pressure is less.

Diagram of Pressure.—Draw a horizontal line and divide it into degrees Centigrade and Fahrenheit to represent the temperature of the vapour. Draw vertical lines representing to a convenient scale the amount of depression of the mercury which measures the vapour pressure. Then if the ends of these lines be joined by a curve, and diagonal scales be provided, the pressure at any temperature can be accurately read.

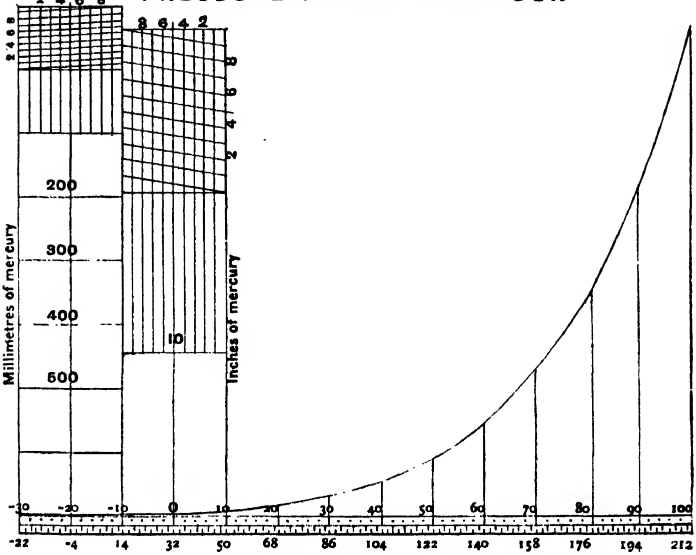
The diagrams (Fig. 39) are drawn from the results obtained by Regnault, which have been recently confirmed by the careful observations of Professors Ramsay and Young.

The experiments of Dalton and the accurate values of the amount of water pressure obtained by these physicists confirm the conclusion to which the simple experiments led up, that the pressure of water vapour depends on the temperature.

It should here be observed that this is not a repetition of Charles's Law (p. 265). If the vapour were a gas whose pressure increases only in consequence of increase of temperature, the curve would be a straight line (coefficient of expansion ·0036 C. and ·002 F.).

The diagrams give the pressure of saturated water vapour.

PRESSURE OF WATER VAPOUR



EXAGGERATION OF THE PORTION -35 TO 30C

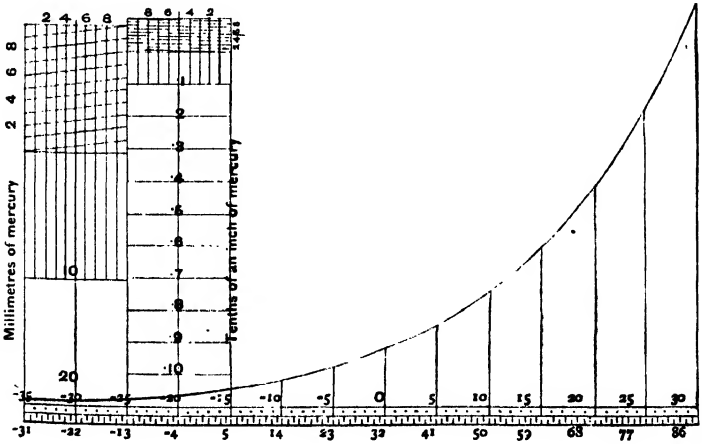


Fig 39. Diagrams of water-vapour pressure.

Saturated vapour is that which is formed in a closed space in the presence of its liquid.

Before proceeding to the discussion of what are the characteristics of saturated and unsaturated vapours, it will be well to speak of the vapours of some other liquids besides water.

Vapours of Various Liquids.—The pressure of saturated vapours at the same temperature differs with the nature of the vapour or evaporated liquid.

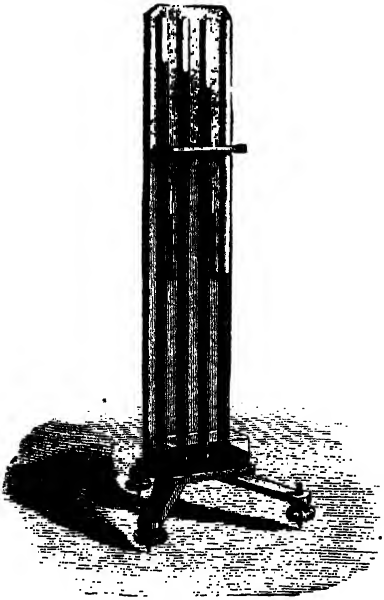


Fig. 40.—Different vapours.

Let four barometer tubes be set up side by side in the same cistern as shown in Fig. 40. At the commencement of the experiment there is a Torricellian vacuum in each, and all stand at the same height. Leave the left-hand tube for a column of reference, and into the second from the left introduce some water by means of a syringe or pipette as before; into the third, some alcohol; and into the fourth, some ether.

The columns are not equally depressed by the vapours formed, the temperature being the same, 68° F. (20° C.) in the figure. The water vapour exerts a pressure measured by ·68 in. (17 mm.) of mercury; alcohol vapour, 1·76 in. (44 mm.); ether vapour, 17·3 in. (434 mm.).

The experiments may be carried further by using other liquids or by immersing the whole apparatus in a bath or closed air chamber, whose temperature can be varied. Such experiments show that the pressure of saturated vapours varies with the

temperature and the nature of the liquid evaporated. A diagram similar to Fig. 39 can be drawn for each liquid.

Volatile Liquids are those which are easily volatilised or evaporated. When a liquid has a large vapour pressure at ordinary temperatures, as is the case with ether, alcohol, and the essences, perfumes, etc., the liquid easily flies off in vapour and is called *volatile.* Some physicists use the term of all liquids which can be evaporated, in contradistinction to those, such as glycerine, oil, etc., which cannot. In this sense mercury is volatile; its vapour pressure at 212° F. (100° C.) is ·03 in. (·75 mm.) of mercury, in the other sense it is not volatile.

Saturated Vapour.—Fill a long barometer tube with mercury and invert it into a deep trough (HYDROSTATICS, Figs. 22, 23), thus forming a barometer. Now admit a small quantity of some liquid—water, or preferably some volatile liquid, such as ether or alcohol, into the tube; it evaporates in the vacuum and depresses the column. The barometer tube should be held with a cloth or flannel to avoid heating it with the hand. So long as there is liquid in the tube above the mercury the column remains at the same height above the mercury in the trough, whether the tube be moved up or down. The vapour is 'saturated,' being in the presence of its liquid, and it exerts the same pressure, however much space is allowed for it in the top of the tube. If the tube is raised and more space is available, more liquid is evaporated; if the tube is lowered some of the vapour is condensed. In neither case is the pressure altered so long as the temperature is the same and there is liquid above the mercury.

The experiments which have been described show that at a given temperature there is for every liquid a certain pressure which its saturated vapour exerts, and this is the maximum pressure which the vapour at that temperature can exert.

Unsaturated Vapour.—In the experiment described above a small quantity of liquid only was introduced. As the tube is raised and space is afforded to the vapour, the pressure continues the same until this liquid is all evaporated. When the tube is further raised and there is no more liquid, the same conditions

no longer prevail. The vapour is unsaturated, and it no longer exerts the same pressure on the mercury. The behaviour of the mercury column is then exactly similar to that described in HYDROSTATICS, p. 172. Unsaturated vapours behave like gases, and obey Boyle's Law of Pressures.

The so-called 'permanent' gases are really unsaturated vapours. Take air as an example, liquid air being now so frequently spoken of. Above the liquid air in the vacuum-jacketed chamber the air is a saturated vapour at a temperature about $-210°$ C. Air at ordinary temperatures has an immensely great saturated vapour pressure, and at atmospheric pressure air is an unsaturated vapour.

Adiabatic Expansion (ἀ διαβαίνω, not passing). In the foregoing experiments no attempt was made to prevent gain or loss of heat by the vapour when expanding beyond the precaution of holding the tube with a cloth. When no heat passes to or from the expanding vapour the expansion is called *adiabatic.*

If steam expands adiabatically some of it must be condensed into minute spherules of water, forming a cloud, or as a deposit of dew on the surface of the containing vessel.

This is what occurs in Nature when the vapour streaming up from the earth into the upper air expands in consequence of a decrease of pressure. The same takes place in the steam-engine when working expansively. If dry saturated steam at 115 lbs. on the square inch at a temperature of 338° F. is expanded until the steam is at a pressure of 20·8 lbs. and a temperature of 230° F., it occupies a volume five times as great: but just one-tenth of the originally dry steam is condensed.

Critical Temperature.—For each gas there is a temperature called the *Critical Temperature*, and when the gas is above this point it is not possible to liquefy it by any pressure, however great. This important principle was discovered by Dr. Andrewes.

When a vapour is saturated, any diminution of the space it occupies does not increase its pressure but causes condensation; but in the case of a gas above its critical temperature, at no pressure, however great, is this condition reached.

The components of the atmosphere have different critical temperatures: oxygen, $-118{\cdot}8$ C.; nitrogen, $-146{\cdot}0$ C.; argon, $-121{\cdot}0$ C., and the pressure under which they liquefy at the critical temperature also varies: oxygen, 50·8 atmospheres; nitrogen, 35 atmo.; argon, 50·6 atmo.

At ordinary temperatures air behaves as if its saturated vapour pressure were infinite.

Vapours and Gases.—Dr. Andrewes' critical temperature enables us to discriminate between vapours and gases. A *vapour* is a gas whose critical temperature is within the range of ordinary terrestrial temperatures. A 'permanent' *gas* is one (whose critical temperature is not within the ordinary terrestrial range of temperature, that is to say) which, at ordinary temperatures, is not condensable into liquid by pressure only.

Carbonic acid is the only 'gas' which has a critical temperature within the ordinary range, viz. 30·92° C. (87·67° F.). Strictly speaking, according to the definition it is a vapour; but compare carbonic acid with the vapour of a very volatile liquid, say ether. Ether vapour can be liquefied at a temperature of 15° C. by a pressure of half an atmosphere, while at a temperature of 15° C. carbonic acid requires a pressure of 50 atmospheres to liquefy it.

Hydrogen has the lowest critical temperature, $-243°$ C. (30 C. *abs.*); boiling point 21 C. *abs.*; melting point 16 C. *abs.* It was liquefied by Prof. Dewar on May 10, 1898, and shown as a solid by him at the Centenary Celebration of the Royal Institution in June 1899.

With regard to the deviation of gases from Boyle's Law, referred to in HYDROSTATICS, p. 175, different gases behave in the same way if the temperature and pressure be measured, not in the ordinary units—degrees, dynes, cm. etc.—but in fractional parts of the critical temperature (*abs.*) and of the critical pressure.

The minimum value of the product of pressure and volume and its position is the same for all gases when reckoned in terms of their critical values. For example, Hydrogen at $-183°$ C. acts like air at 0° C.

Mixture of Gases and Vapours.—The experiments at the

beginning of the chapter made it quite evident that in the atmosphere water vapour is mixed with the air. On the other hand, the more careful experiments for measuring the vapour pressure have all dealt with evaporation in a vacuum. What has now to be considered is the mixture of gas and vapour.

Unsaturated water vapour behaves like a gas, and it has been shown in HYDROSTATICS, p. 174, that where there is no pressure there is no gas. Hence, since there is water vapour present in the atmosphere it is evident that even in the open air the water vapour present must exert some pressure.

Resuming the experiments of p. 325 with the deep trough; When the long barometer tube has been filled with mercury and inverted into the trough, introduce into the vacuum sufficient *dry* air to fill about 4 inches at the top of the tube when at atmospheric pressure, and raise the tube so that the air is expanded to occupy 8 inches. The mercury column then stands at half the barometric height.

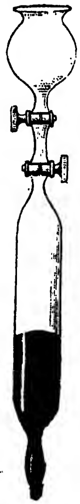


Fig. 41. Voluminometer addition.

Now introduce some water into the tube; when it reaches the air space some of it is evaporated and the column of mercury sinks, showing that the vapour exerts pressure on the mercury.

The evaporation is not instantaneous, as in the case of a vacuum. After a little time the space is filled with saturated vapour mixed with air at half the atmospheric pressure, and the mercury column is depressed by the pressure of the vapour. If there be not sufficient water for the air to be saturated, the pressure is less.

What the experiment shows is that in a mixture of air and water vapour each exerts its own pressure independently.

Voluminometer Method.—The measurement of pressures with the barometer tube and deep trough is cumbrous and inaccurate; careful experiments can be much more easily carried out with the voluminometer, which is used to prove Boyle's law (HYDROSTATICS, p. 174), with the

addition of tube and stopcocks shown in Fig. 41 instead of the closed tube B.

In the lower stop-cock there is a passage which goes only half way through the tap, and by its means liquid may be introduced into the closed tube which takes the place of B. Also the closed tube can be placed in a bath of water so that the temperature of its contents can be varied and ascertained.

The flexible tube is filled with mercury and the closed tube with *dry* air which occupies about 4 cubic inches when at atmospheric pressure, that is when the mercury stands at the same height in the two arms.

Introduce through the stop-cock sufficient water for some to remain unevaporated. The column at B is depressed by the pressure of the vapour. Now raise A until the volume of the saturated air in B is the same as that of the dry air at first (HYDROSTATICS, Fig. 24); the height of the column at A above B is that due to the pressure of the vapour. The temperature is kept constant throughout the experiment, and the pressure of the water vapour corresponds to the temperature (see p. 323).

If the air in B be expanded by lowering A, or if it be compressed by raising A and lowering B, the mercury column between B and A always has additional height due to the vapour pressure, besides the fractional part of the barometric height, which causes the compression of the air, according to Boyle's Law of Pressures.

If there be sufficient water in B the air is always saturated. When the volume of the air space B is increased more liquid is evaporated to fill it; when the volume of the air space is diminished some of the vapour is condensed. The pressure remains the same in all cases.

Dalton's Laws of Vapours may now be recapitulated.

1. The pressure of saturated vapour depends only on the temperature and the nature of the liquid.

2. In a mixture of gases and vapours each exerts its own pressure independently of others present, provided that they do not act on one another chemically. This is sometimes described by saying that one gas acts as a vacuum to another.

CHAPTER VIII

Boiling—Latent Heat of Evaporation

Ebullition or Boiling—Boiling Point—Determination of Heights—Cooking on Mountains—Boiling at High Pressure—Ebullition of Brine—Distillation—Latent Heat of Evaporation—Total Heat of Evaporation—Determination of Latent Heat—Latent Heat of Steam—Cooling by Evaporation—Hysteresis—Spheroidal State.

Ebullition or Boiling.—When heat is applied at the bottom of a vessel containing liquid, water for example, the water is warmed and rises, cooler liquid flowing down to take its place. Convection currents are set up and the whole is heated (see p. 287). As the temperature rises, more and more vapour is given off into the heated space above the water, and rising into the cooler air is condensed, so that it becomes visible in a cloudy form; but the water is not yet boiling.

The surface of the vessel where the heat is applied is usually called the 'heating surface'; it may not be actually at the bottom. As the water becomes hotter, some of it in contact with this surface is vaporised. Any bubble of steam formed there must have a vapour pressure which is equal to the fluid pressure there or it could not exist as a bubble.

Now at any point in a liquid the fluid pressure is equal to the pressure on the surface, together with that due to the depth of the liquid, which last need not be considered in the present inquiry. The pressure in the bubble must at least equal the external pressure, and water vapour at a certain pressure must have a definite temperature (see p. 323), *e.g.* the bubble formed at

a pressure of one atmosphere must have a temperature 100° C. (212° F.); if the water be cooler than this, the bubble is condensed as it rises.

This is what takes place when a kettle is 'singing'; small bubbles of steam are formed and condensed as they rise. The walls of the bubble meet with a sharp impact; the noise made in a 'water hammer' illustrates the effect of the surfaces of water meeting without any air to cushion them. These bubbles impart their heat to the water above, and the singing gradually ceases. When the temperature of the water is equal to the

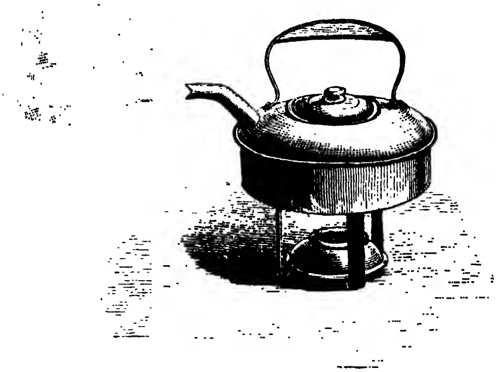


Fig. 42.—Boiling kettle.

temperature of water vapour of a pressure equal to that in the water, the bubbles of steam formed at the heating surface are no longer condensed, and steam is freely given off (Fig. 42).

Boiling or Ebullition is the formation and discharge into saturated space of vapour formed in a liquid at the temperature of saturated vapour corresponding to the pressure in the liquid.

Thus *boiling is distinguished from evaporation*, which is the formation of vapour at the surface of a liquid when the space above it is not saturated.

The Boiling Point of a liquid is the temperature of saturated vapour at the pressure in the liquid.

The description of the process of boiling water given above should make it clear that so long as the vapour is free to escape it does not increase the pressure on the liquid, the temperature of the liquid does not rise above the boiling point but remains at that temperature until all the liquid is boiled away.

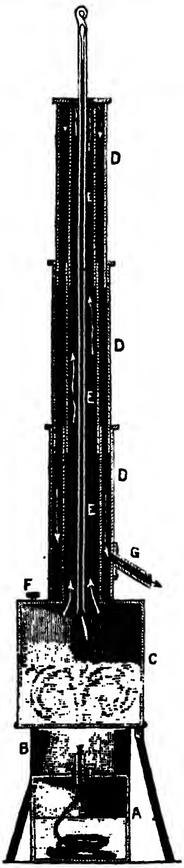


Fig. 43.—Hypsometer.

When water or any liquid is boiling in the open air, it is the atmospheric pressure which is the external pressure on the liquid. It is at this pressure that the vapour is formed, and when the water is at the temperature corresponding to this pressure the vapour escapes freely and the liquid boils.

Consequently the temperature at which a liquid boils in the open air depends on the atmospheric pressure.

If the pressure on the surface of the liquid be reduced, the vapour is formed and given off freely at a lower temperature, *i.e.* the boiling point is lowered.

Determination of Heights. — Since the temperature of water boiling in the open air depends on the atmospheric pressure, it follows that an observation of the temperature at which water boils is equivalent to a reading of the height of the barometer. This fact is made use of to ascertain the height of mountains. An instrument called an Hypsometer (Fig. 43) is provided for the purpose. It is a portable vessel DD, arranged so as to expose a very sensitive thermometer E to the steam escaping from water boiling at atmospheric pressure. In Negretti and Zambra's instruments the spirit lamp A is protected by wire-gauze B, so that it will burn in the open air. The steam from the boiler C passes all round the thermometer E, and then forms

a steam jacket to the tube which contains the thermometer, escaping freely at G. The boiler is filled through F.

The table of vapour pressures (Fig. 39) shows the readings of the barometer corresponding to the temperature of boiling water. The hypsometrical rule (HYDROSTATICS, p. 191) gives the altitude corresponding to the reading of the barometer, on the assumption that a barometer at the sea-level stands at 760 mm. (29·92 in.). A combination of the two gives the altitude corresponding to the temperature of boiling water. The advantage of this method of ascertaining heights is that it is easier to carry thermometers than barometers on mountain expeditions, but the method fails in accuracy.

Mr. Whymper, whose 'Travels amongst the Andes' were undertaken with a scientific object, has reported very strongly against it. He argues that in the matter of accuracy it cannot be compared with a reading of a mercurial barometer. At the sea-level the value of a degree Fahrenheit is about 531 feet, while at the summit of Mt. Blanc it is about 600 ft., so that a very small degree of accuracy can be attained. Besides this, he found that the mean of boiling point observations at three stations above 19,000 feet showed an error of 513 ft., which even led him to cast a doubt on the pressure tables of Regnault.

Cooking on Mountains.—The low temperatures at which water boils under reduced pressure interferes with cooking at great altitudes. At a height of 18,000 ft. water cannot be heated in open vessels above 180° F., and this is not hot enough to set the white of an egg.

Boiling at High Pressure.—When water is boiling in a closed vessel and the steam does not escape freely, it exerts a pressure on the surface of the water. This causes increased pressure at the heating surface where the steam is formed and the temperature at which it is formed is raised. From the description of boiling given above, it will be seen that the temperature of boiling is raised as the pressure on the surface rises.

A railway locomotive has safety-valves set to blow off at 180 lbs. on the square inch; when running, steam is rapidly

made and used at nearly that pressure. The engine-driver, when running into a station, reduces the fire and injects cold water, so that the pressure in the boiler is reduced perhaps to 160 lbs., and the temperature of the water correspondingly lowered. When the steam is shut off the pressure rises and no steam is formed until the whole of the water in the boiler is raised to a temperature corresponding to 180 lbs., the blow-off pressure. This explains, what is sometimes puzzling, the sudden change from rapid formation of steam to rest in a station.

To facilitate the discussion of steam under high pressure an extension of the diagram of vapour pressure is given on a reduced scale and extended to 15 atmospheres (Fig. 46, p. 339). The water in a boiler at a pressure of 300 lbs. on the sq. in. is at a temperature of 414° F. The *Serpollet* boiler, a strong tube completely filled with water, is very highly heated; feed water is pumped in, and the expelled water flashes into steam.

PAPIN'S DIGESTER.—The high temperature of water boiling under high pressure is made use of practically to reduce gelatinous substances, such as calves' feet, for jellies. Strong boilers with safety-valves are found in some kitchens, and as they were introduced by M. Papin they are called after him.

Ebullition of Brine.—Water with solid matter dissolved in it, *e.g.* brine, a mixture of salt and water, boils under atmospheric pressure at a higher temperature than water alone. Pure water vapour is given off at the temperature of the liquid.

Distillation.—Evaporation is largely used to obtain liquid in a state of purity. If two liquids are mixed the more volatile of them will be vaporised first, leaving the less volatile behind. Or if there are impurities in water, *e.g.* salts in solution, the liquid evaporates and leaves the solid matter behind.

The former principle is used in the distillation of spirits from wine or fermented liquors.

A rude still, shown in Fig. 44, is seen in a Highland bothy. The big kettle on the fire contains fermented malt liquor. The spirit vapour is led from the kettle through the 'worm,' which is kept cool by the cold spring water flowing over it. The

products of distillation, a coarse whisky, are seen dripping into the keg.

The latter principle is used in the apparatus so generally fitted in ships for procuring fresh from sea-water.

Normandy's condensers and feed-water evaporators are used for this purpose. The steam from the main boilers, which may be itself greasy and impure, is used to vaporise the sea-water in the evaporators, the steam thus driven off is condensed as pure water. If the water is to be used for drinking purposes sufficient mineral salts should be added to make it palatable, and if in

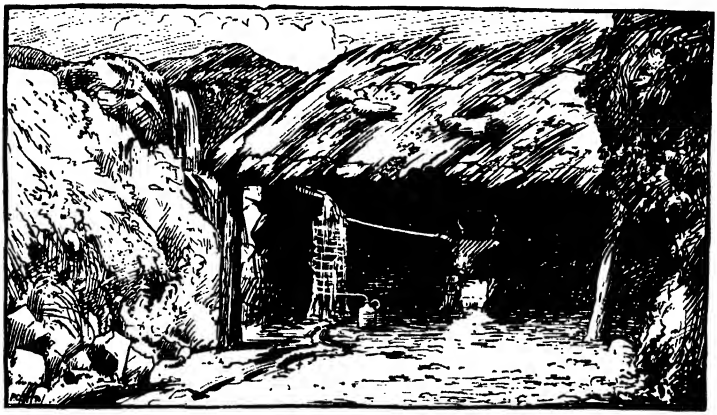


Fig. 44.—Illicit still.

addition it be made to absorb some air and be thoroughly cooled, it is far better than water from the shore which has been kept in tanks.

Latent Heat of Evaporation.—If a flask of water be boiling over a flame it takes some time to boil away. The heat which is continually being applied to it must go somewhere, for it does not raise the temperature of the water, as this remains continually at the boiling point.

If there be six other flasks, each containing the same amount of water, and all at the temperature of the room, 16° C. (62° F.), they may each in turn be raised to the boiling point, 100° C.

(212° F.), over a similar flame, while the water in the original flask is being boiled away; that is to say, six equal quantities of water can be raised through 84° C. or 150° F. by the application of a quantity of heat which causes an equal quantity at 100° C. to evaporate.

From this experiment, which is of course a very rough one, it may be gathered that about 500° C. and 900° F. heat units disappear in changing water at the boiling point into steam at the same temperature. The heat which is applied to liquid at the boiling point to change it into vapour is called the Latent Heat of Evaporation.

Total Heat of Evaporation.—It is sometimes convenient to know the amount of heat which must be added to a liquid at the freezing point in order to evaporate it, and this is called the Total Heat of Evaporation.

It is the sum of the sensible heat which raises the temperature of the liquid, and the latent heat of vaporisation which does work in causing the liquid to change its state.

There is work done in evaporating a liquid which is not internal work, though it is almost always included in the latent heat. Saturated vapour at any given pressure occupies a much larger space than liquid, and in the act of evaporating it must have done external work against this pressure.

Determination of Latent Heat of steam at atmospheric pressure—*Calorimeter method.*—The steam from water boiling in a retort is led through a helical pipe called a 'worm,' terminating in a reservoir C. The worm is placed in a calorimeter (Fig. 45) and surrounded by water, so that the steam is condensed and the water warmed; a stirrer S and thermometer are provided to ensure all the water being at a uniform temperature and to register it. If a certain quantity of water be evaporated, and the quantity of water in the calorimeter and its rise of temperature be known, the latent heat of steam can be computed.

The end of the worm is open to the air, through the pipe P, so the steam must be at atmospheric pressure; the condensed water collected in the reservoir C is drawn off and weighed.

Precautions must be taken that no heat be conveyed directly from the lamp to the calorimeter; also that no water be carried with the steam into the worm owing to violent ebullition.

Details of an actual experiment will serve to show the process of determination.

Weight of calorimeter empty . . .	319 grammes.
,, ,, full	1165 ,,
,, water	846 ,,
Temperature of water	17° C. (62° F.).
Water equivalent of calorimeter . . .	30 gr.

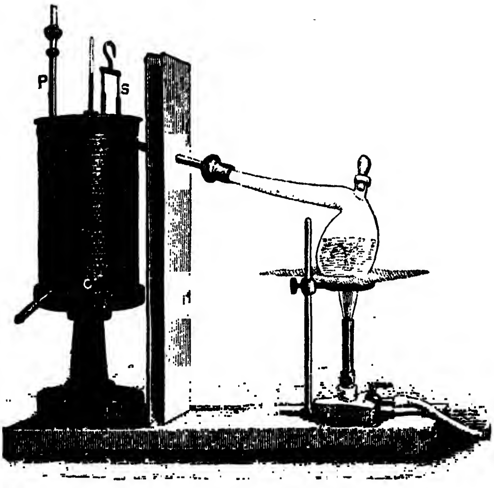


Fig. 45.—Steam calorimeter.

Steam is now passed through the calorimeter; a thermometer in the retort checks the temperature of the steam given off as 100° C.

After some time the experiment is stopped.

Amount of water condensed . . .	10 gr.
Temperature of calorimeter . . .	24° C. (75° F.).
Rise of temperature	7° C. (13° F.).
Amount of water raised 7° C. including calorimeter	876 gr.
Number of heat units gained by water and calorimeter	6132 C.; 11388 F.

Amount of sensible heat lost by 10 gr. of steam condensed and cooled to 24° C.	760 C.; 1370 F.
Amount of heat not accounted for above, given up by 10 gr. of steam when condensed	5372 C.; 10018 F.
Latent heat of steam	537·2 C.; 1001·8 F.

Lecture-room apparatus cannot be expected to give accurate results, and the value deduced may be expected only to be approximate. The latent heat of steam at standard atmospheric pressure is 523·6 C. (966 F.).

With this apparatus the latent heat of steam at atmospheric pressure alone can be obtained.

Latent Heat of Steam at Various Pressures.—The latent heat of steam is different at different pressures; its value under varying pressures and temperatures was obtained by Regnault by means of suitable apparatus. A diagram showing the results which he obtained is given in Fig. 46.

The practice in the use of diagonal scales afforded above should enable any one to read off the various values accurately. In this diagram are given—the pressure of steam; the specific volume of steam; the total heat and latent heat of steam at various pressures and temperatures from 0° C. to 200° C. Their values can be taken off in various units, and thus four pages at least of closely printed figures are avoided.

The words LATENT HEAT do not appear, as they might cause confusion. The vertical distance between the curves of sensible heat and total heat gives the latent heat at the temperature given at the head of the figure.

There is a dotted line above the sensible heat line—the vertical distance between this and the sensible heat line is the work done by the vapour in expanding against the pressure at that temperature, and between the dotted line and total heat the molecular work done in the change of state—the true latent heat.

Cooling by Evaporation.—Whenever any portion of a liquid evaporates, some heat must become latent. This may be supplied from outside, as when damp linen is dried before a fire. When

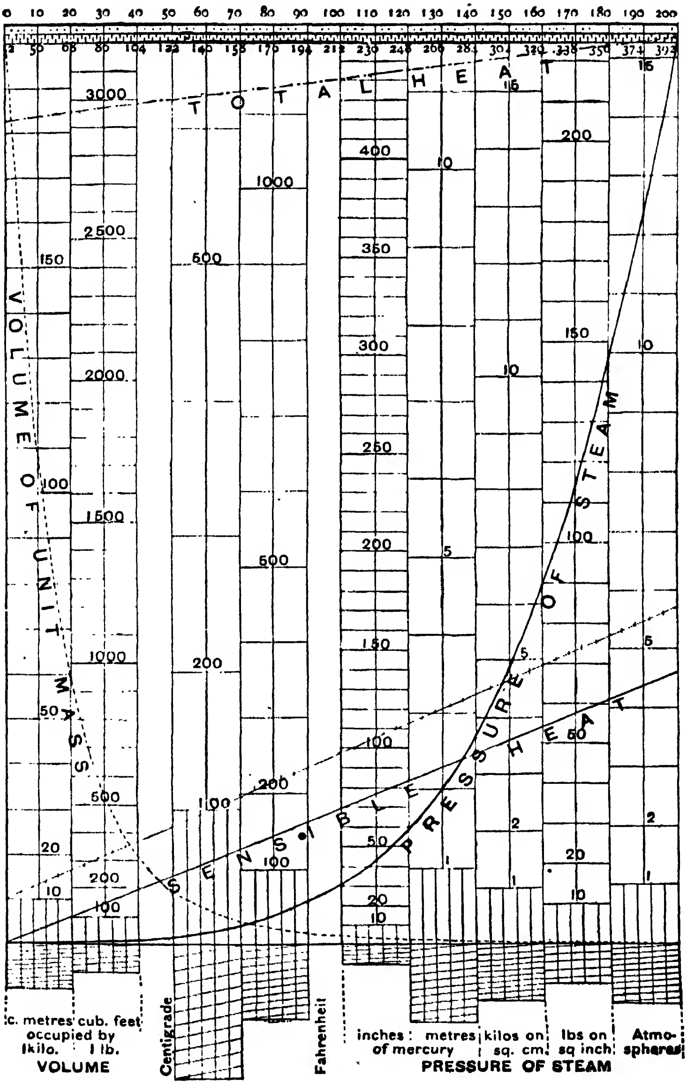


Fig. 46.—Latent heat, pressure, and volume diagram.

sufficient heat is not supplied, some of the sensible heat in the neighbourhood is taken and the temperature of surrounding objects is lowered; as for example when eau-de-Cologne is used to cool the forehead.

Liquid evaporates into unsaturated space, and whatever causes rapid evaporation causes cooling.

1. *Volatile liquids* evaporate more quickly than others in the same circumstances. Alcohol or ether produce a sensation of cold when placed on the skin; their use for the purpose of cooling will be referred to below.

2. *Warmth increases evaporation* and may cause cooling. Heated air will hold more moisture than cold air, and consequently evaporation proceeds more rapidly into hot air, while the heat rendered latent may not be wholly supplied by the air, and cooling may ensue.

In hot countries water is put into a porous jar or *alcarraza*; the water exudes from the surface and evaporates, and the water inside is cooled.

Damp clothes have a chilling effect on the skin; the evaporation reduces the temperature of the body in a dangerous manner.

3. *Wind increases evaporation.*—The layer of air nearest to water or a wet substance is very speedily saturated with water vapour. If no motion takes place in the air and the saturated layer remains next the water there is no further evaporation; a current of air removes the saturated layer and further evaporation proceeds into the dry air.

Causes 2 and 3 explain the way in which clothes are dried before a fire or in a wind. It is most essential in a drying room to provide for a steady current of air ensuring the entrance of fresh air and the exit of damp air; for if the room were filled with saturated air no further drying would go on at that temperature. Heat is advantageous, but a current of air is more so.

The action of a current of air explains the danger caused by 'a draught.' The draughty air may be no cooler than that of

the room, it may even be hotter, but playing upon the skin it induces rapid evaporation of the bodily moisture; the temperature of the body is lowered and 'a cold is caught.'

A striking experiment illustrates this. Some water is placed in a wooden saucer, as that does not allow heat to pass easily through it to the water. A thin copper saucer is floated on the water and some ether is put in it. The ether is blown with a bellows. Evaporation of the ether proceeds rapidly because the air is removed before it becomes saturated with vapour. The evaporating ether removes sensible heat from the water through the copper so rapidly that the water is frozen.

4. *Decrease of pressure increases evaporation.*—Evaporation from the surface of a liquid is rendered more rapid by reducing the pressure on it. This is due to two distinct causes. First,

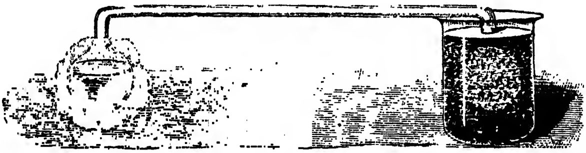


Fig. 47.—Cryophorus.

evaporation in a vacuum, such as that in a barometer tube, is almost instantaneous, and if in the presence of its vapour only liquid evaporates very rapidly until the vapour is at saturation pressure. If the vapour pressure be diminished evaporation is more rapid. The second cause is the action of the air in retarding the diffusion of vapour. The layer of air next to a liquid surface is always in a state of saturation; but the air acts as a check on the spread of the vapour, and it has to 'diffuse itself through the air by a kind of percolation' (Clerk-Maxwell). If the density of the air be reduced, the evaporation proceeds more rapidly.

The first of these causes can be shown by two experiments.

The Cryophorus.—Two glass bulbs are connected by a glass tube (Fig. 47). One of the bulbs is half filled with water, and before the apparatus is sealed the water is boiled in it, so

that all the air is expelled and nothing but water vapour is left in the tube and the empty bulb. The whole instrument being cool the bulb with the water in it is wrapped in cotton wool to protect it from any access of heat, and the empty bulb is plunged into a freezing mixture. The vapour in it is condensed, the pressure on the water reduced, and evaporation proceeds rapidly in the other bulb. For the production of vapour sensible heat is taken from the water and rendered latent, so that the water is cooled and ice appears in it. Freezing is carried out on a large scale by the 'ammonia process.' Water absorbs 700 times its volume of ammonia gas; when this is given off a fall of temperature follows as above.

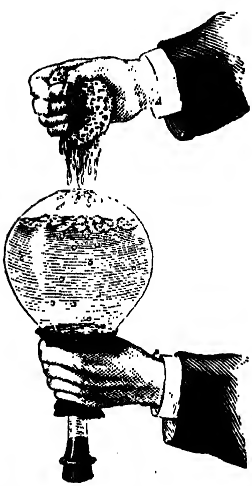


Fig. 48.—Reduction of pressure.

Water is boiled in a strong flask over a spirit lamp, and when little below the boiling point the flask is corked, and held inverted as shown in Fig. 48.

A sponge full of cold water is squeezed over the upturned bottom of the flask; immediately bubbles of steam are given off freely; in fact, the water seems to boil because it is cooled. What really occurs is that the vapour in the flask is condensed, and the vapour pressure being diminished the boiling point is lowered and evaporation is very rapid.

In his experiments on liquid air (1894) Professor Dewar used the rapid evaporation of ethelyne for the production of a temperature of – 200° C. Before his introduction of the vacuum jacketed reservoir liquid oxygen had been shown in a lecture room kept at a low temperature by its own evaporation at the atmospheric pressure.

The second cause of rapid evaporation by decrease of pressure is shown by placing a beaker of water at 90° C. under the receiver of an air-pump. The water evaporates rapidly and

appears to boil as the pressure is removed by a few strokes of the pump. The air which checks the diffusion of the vapour is rarefied and the vapour pressure is also diminished by removal of vapour.

Hysteresis (*Hesitation*).—A liquid may be reduced below the freezing point, but if no movement takes place it does not solidify. It seems as though all parts of the liquid having an equal right to freeze, no part can take the lead by parting with its latent heat to another.

Distilled water in a test tube is surrounded by water to which a freezing mixture is carefully added so as to reduce the temperature slowly without causing motion in the test tube. If a thermometer be now plunged into the test tube it may indicate a temperature as low as 25° F. (– 4° C.) without freezing having taken place. But immediately the thermometer enters ice-crystals are seen to form like spikes, protruding from the bulb of the thermometer. The water freezes and the temperature rises; the latent heat given up by the water as it freezes becomes sensible, raising the temperature of the rest.

The same hesitation occurs in the change of state from liquid to gas. If pure water, which has been previously boiled to free it from air, is placed in a clean smooth vessel, and heated slowly in a sand bath, it may be raised to 110° C. without boiling. Then some of it vaporises with explosive violence, and the temperature is reduced to 100° C., because sensible heat is rendered latent. This occurs at intervals, if heat is continually applied, and is called 'boiling with bumping.' In the course of experiments water has been raised to 135° C. without boiling; when, on the sudden outburst of steam, the temperature was lowered to the boiling point.

An instance of the same kind of hesitation is seen in the condensation of vapour. A vapour can be reduced below the temperature at which it is saturated. Unless there be some points on which it can settle, no part of it seems able to condense first, and it is then 'supersaturated.'

Mr. Aitken's experiments on fogs and clouds have shown

that in a fog each spherule of water has been formed round some solid nucleus.

Spheroidal State.—If a drop of water is let fall on a red-hot iron plate, it is not at once turned to steam, but runs about the plate in a spheroidal form. If the water were really in contact with the iron it would be vaporised at once; but the drop is surrounded with a shell of vapour which forms a non-conducting envelope and prevents the heat of the plate from reaching the drop.

In proof of this, a light which is on the further side can be seen between the drop and the plate, showing that they are not in contact.

A strong copper vessel is heated to redness over a spirit or Bunsen flame and a little water is put in it. The water assuming the spheroidal state is not vaporised. But as the vessel cools the water touches the copper and instantly flies off in vapour explosively; this apparatus is often used to illustrate boiler explosions.

CHAPTER IX

Hygrometry and the Weather

Amount of Water Vapour in Air—Humidity of the Air—Drying Power of the Air—Relative Humidity—Pressure of Water Vapour in Air—Dew Point—Hygrometry—Hygrometers—Hygroscopes—Variation in Amount of Vapour—Different Altitudes—Dew—Clouds—Snow, Hail, and Rain—Rain Gauge—Weather Indications.

The weather often affords a topic of conversation in our variable climate because of the way in which its changes influence our life. The warmth or cold, the dryness or dampness of the atmosphere affect our feelings and our health so much that they attract our attention. And when we find that these conditions of the atmosphere also affect the weather, the subject of Hygrometry becomes doubly interesting; for *Hygrometry* (ὑγρὸς, damp) *is the science which deals with the dampness of the air.*

That there is always a considerable amount of water vapour in the open air is shown by the simplest experiments. The moisture condensed on a tumbler of cold water is evidence that there is water in the air which cannot be seen. If a saucer containing sulphuric acid be left open to the air, it increases in weight, having imbibed water from the air. Sulphuric acid in common with some other substances has the property of combining readily with water.

Amount of Water Vapour in the Air.—Sulphuric acid and calcium chloride having this property of absorbing water can be used to remove all the water from air which is near them.

Tubes D filled with calcium chloride (Fig. 49) or pumice soaked in sulphuric acid are called 'drying tubes,'—three different kinds are shown; if air be drawn through them they are found to increase in weight because they remove all the water from the air. The volume of air drawn through the tubes is measured by using an 'aspirator' A. This is a vessel of known volume filled with water; when a tap at the bottom is opened the water flows out, drawing in the air through a tube at the top. If a known volume of air be drawn through a set of drying tubes the increase in weight of the tubes gives the amount of moisture in the form of vapour contained in that volume of air.

Humidity of the Air.—The density of the water vapour in

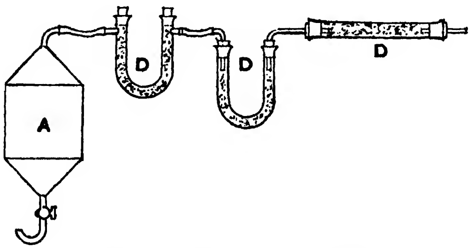


Fig. 49.—Drying tubes and aspirator.

the air is called the *Humidity of the Air;* it varies from 1 grain per cub. ft. on a cold dry day to 10 grains per cub. ft. on a day of tropical heat and dampness.

The density of saturated vapour varies with the temperature, and is given by the curve of Specific Volume in the diagram of vapour pressures (Fig. 46). The ordinates of this curve give the numerical values determined by Regnault. For example, at a temperature of 15° C. (59° F.) a lb. of water vapour occupies 1284 cub. ft., hence a cub. ft. of vapour weighs 5·5 grains; the vapour exerts a pressure supporting ·518 inches of mercury.

Drying Power of the Air.—As water evaporates so long as the space above it is not saturated, the drying power of the air is measured by the weight of water vapour which will bring a cubic foot of air up to saturation at that temperature. This is

evidently the difference between the density of the vapour present in the air and the density of saturated vapour at that temperature.

Relative Humidity.—It is a common remark to make, 'the air is very dry,' when water evaporates freely, and in consequence wet clothing dries rapidly; or we say, 'the air is very damp' when wet things dry slowly or not at all. We call the air 'dry' when it is far from saturation, and 'damp' when it is nearly saturated. The relative humidity is the ratio of the density of the vapour in the air to the density of saturated vapour.

The relative humidity and the drying power of the air are numerical estimates of what our senses feel as the dampness and dryness of the air.

Pressure of Water Vapour in the Air.—The water vapour in the air exerts a pressure which depends on its quantity and on the temperature. It was one of Dalton's early conclusions that the pressure of a mixture of gases is the sum of the pressures which they would exert separately, if alone in the space. The pressure of the water vapour can be considered separately, as if the atmosphere consisted of the water vapour alone.

At a given temperature the pressure of water vapour has a certain maximum value, given by Regnault's Tables (p. 323). When the vapour in the air is at this temperature and exerts this pressure its density has a certain value, also given in the Tables as described above; this is the greatest quantity of water which can exist in the air in the form of vapour; the air is then 'saturated.'

If the air become warmer and the vapour pressure remain the same the vapour expands and becomes less dense; the same occurs if the temperature remain the same and the vapour pressure decrease. In either case the amount of water vapour in the cubic foot is decreased, and the air becomes 'unsaturated.' The vapour pressure is then not the maximum for that temperature, or in other words it is the maximum pressure for a temperature below that of the air.

Considering more particularly the experiment with which

Chap. VII. began; let the temperature of the room be 72° F. (22° C.) and the vapour pressure in the room support ·537 in. (13·54 mm.) of mercury. This is the maximum pressure of vapour at a temperature of 61° F. (16° C.), and the density of such vapour is 5·97 grains per cub. ft. Water cannot exist as vapour of this pressure and density at any temperature below 61° F.

Suppose the temperature of the water in the tumbler to be 50° F. (10° C.), the layer of air nearest to the tumbler is cooled to that point, and as vapour at that temperature cannot have a density of more than 4·24 gr. per cub. ft., some vapour is condensed on the glass in the form of 'Dew.' The natural phenomenon of dew will be more fully described later on.

The Dew Point is the temperature at which dew is formed. To the pressure of the water vapour in the air at any time corresponds a temperature given in Regnault's Tables. Water cannot exist as vapour, when exposed to this pressure, if it be below this temperature, and dew must be deposited on any body exposed to this vapour pressure if it be at all below this temperature.

In the glass of water experiment, 61° F. (16° C.) is the dew point, being the temperature corresponding to the vapour pressure ·537 in. (13·54 mm.). So long as the tumbler is below this temperature moisture stands on it; but the condensing vapour imparts its latent heat to this moisture, and the tumbler is warmed by this and by the air of the room. It gradually reaches 61° F. and the condensation ceases; then as it is warmed still further by the air, the moisture is evaporated and the tumbler becomes perfectly dry outside.

The dew point depends on the prevalent pressure of water vapour alone.

Hygrometers are instruments for determining the humidity of the air, that is, the density of the vapour contained in it.

The drying tubes and aspirator described on p. 346 are used to determine the density of the water vapour in the air, and therefore constitute a hygrometer. But the observation is

cumbrous; hence simpler modes of determination are desirable.

Several hygrometers depend on the observation of the dew point, for example:—

Daniell's Hygrometer acts in the same way as the Cryophorus (p. 341), only it contains ether instead of water. It consists of two bulbs joined by a tube; the lower bulb (Fig. 50) is half full of ether and the air has been expelled by boiling, so that the other bulb and the tube contain only ether vapour. The ether bulb is blackened; in the figure some of the black is omitted so as to show the thermometer bulb which is in the ether. The empty bulb has a thin pad of cotton-wool over it; ether poured on this falls over the bulb and evaporates rapidly. The ether vapour in the bulb is condensed and the pressure on the ether being reduced, evaporation proceeds rapidly in the ether bulb, which becomes cooler, as may be seen by the fall of the thermometer in it.

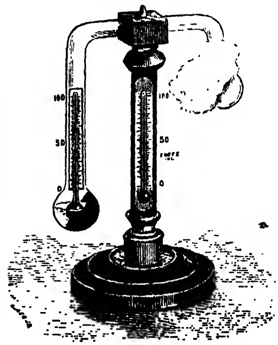


Fig. 50.—Daniell's hygrometer.

At the dew point a dimness, caused by a deposit of dew, appears on the ether bulb. When the bulb is seen to become dull, the thermometer is read and the cooling process is stopped. The surrounding air warms the ether bulb and the dew disappears again from it, when the thermometer is read again. The mean of the temperatures thus read is the dew point.

Care must be taken not to breathe on the bulb nor to allow any part of the body to remain near it, as the moisture in the air is thereby increased locally.

Regnault's Hygrometer.—A tube of highly polished silver, closed at the bottom like a test tube, is filled with ether. Air is blown into the ether, which evaporates and cools rapidly; a thermometer whose bulb is in the ether shows its temperature.

The ether is cooled until dew is deposited on the silver, when the thermometer is read. Cooling is then stopped, and another

reading taken when the dew disappears. The mean of the readings of the thermometer is the dew point.

WET AND DRY BULB THERMOMETERS.—Two thermometers are placed side by side. One of them determines the temperature of the air. The bulb of the other is covered with muslin, which is kept damp by a loose lamp wick conveying water by capillary attraction from a small reservoir (Fig. 51).

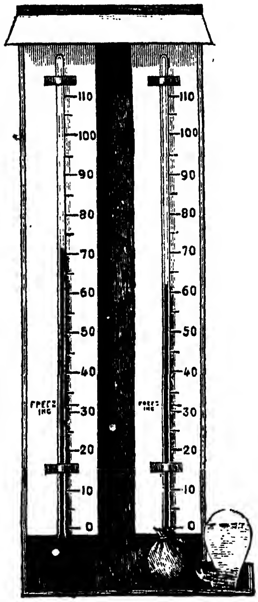


Fig. 51.
Wet and dry bulb thermometers.

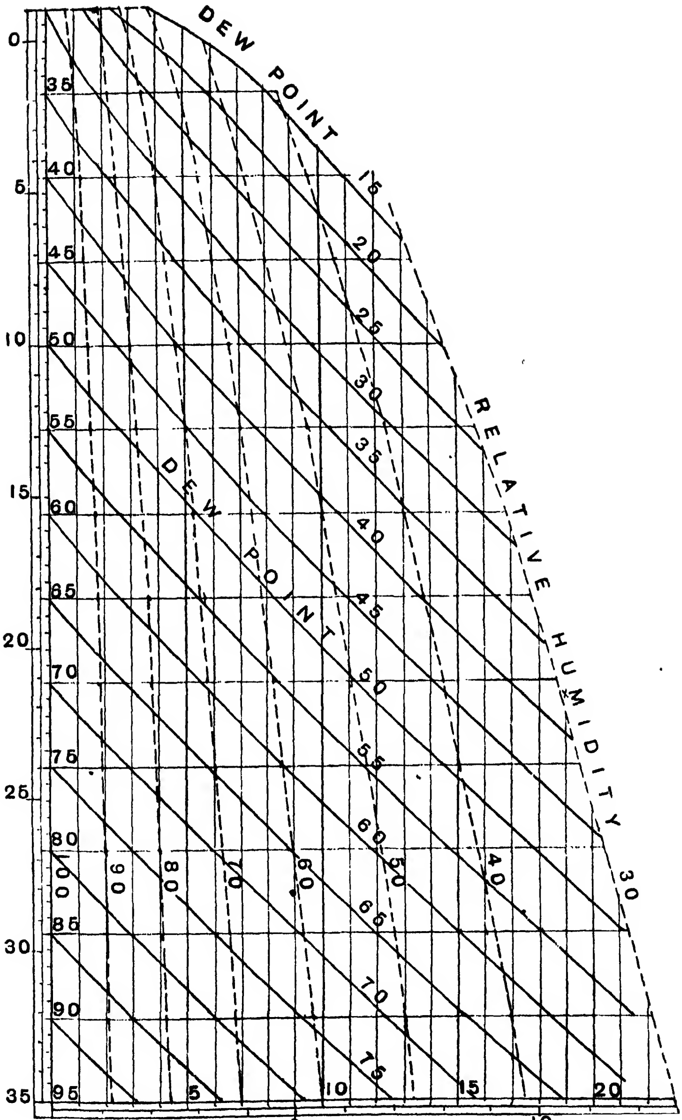
The cotton wick should be frequently changed or cleansed with caustic potash; at an observing station, rain water from the rain gauge is conveniently kept for filling the reservoir.

Moisture evaporates from the muslin more or less quickly according to the drying power of the air. If the air is saturated, no evaporation takes place and the readings of the two thermometers are the same. If the drying power of the air is large, evaporation proceeds rapidly and the wet bulb is cooled to a temperature considerably below that of the dry bulb.

From the comprehensive diagram (Fig. 52), the dew point and relative humidity can be taken off for any readings of the wet and dry bulb thermometers between 32° F. (0° C.) and 95° F., (35° C.).

For instance, the temperature of the air shown by the dry bulb thermometer (Fig. 51) is 71° F., and the reading of the wet bulb thermometer is 52° F., the difference of the two being 19°. This is evidently a very dry day in summer.

Take 71 on the vertical temperature scale and draw a horizontal line through it to meet a vertical line through 19 on the horizontal difference-scale in the point X. This point is between the dew point gradients 35 and 40, and shows the dew



Temperature of Air on left cuts ordinate on difference of wet & dry bulbs in a point indicating Dew Point and Relative Humidity.

Fig. 52.—DEW POINT AND RELATIVE HUMIDITY DIAGRAM

point to be 37°: X is just outside the humidity gradient 30, indicating the relative humidity as 29.

Thus the dew point and relative humidity corresponding to any reading of the wet and dry bulbs can be seen at a glance, or taken as accurately as desired, from the diagram.

Hygrometry.—On the temperature and relative humidity of the air depends to a great extent our bodily comfort. The feeling both of heat and cold is accentuated by an excess of moisture in the air. The brisk feeling in dry mountain air and the lassitude felt in the damp atmosphere of Colombo or Singapore do not depend only on the temperature of the air.

Besides this, the probability of rain coming in a short time is increased if the air is near the point of saturation.

Hence the amount of water vapour in the air is a matter of great moment to those who take an intelligent interest in the weather. This information regarding the atmosphere on the preceding day is given daily in the *Times*. The following table appeared in the issue of October 2nd, 1907, showing the

TEMPERATURE AND HYGROMETRIC CONDITION OF THE AIR IN LONDON (WESTMINSTER) FROM READINGS OF THE DRY AND WET BULB THERMOMETERS. (OBSERVATIONS SUPPLIED BY THE METEOROLOGICAL OFFICE.)

TUESDAY, OCTOBER 1.

Time.	Temperature. Air. Dry Bulb.	Temperature. Air. Wet Bulb.	Temperature. Dew Point.	Pressure of Vapour.	Relative Humidity (Saturation=100)	Weight of Vapour in 10 cubic feet of Air.	Drying Power of Air (per 10 cubic feet).
	Deg.	Deg.	Deg.	Inch.	Per cent.	Grains.	Grains.
8 A.M.	60·2	58·1	56·2	·453	88	51	7
2 P.M.	63·3	58·2	54·0	·417	71	46	18
6 P.M.	61·0	59·0	57·3	·470	88	52	8

Min. temperature, 58 deg. Max. temperature, 68 deg.

Here the features of the atmosphere which we have been considering are given at three different times of the day.

It will be useful to the reader to refer to the humidity diagram on p. 351, to mark on it the readings given here, and

to deduce independently from the diagram the dew point and relative humidity. This will give confidence in the use of that diagram to interpret the readings of the wet and dry bulb thermometers.

At 2 p.m., the dew point being 54° F., reference to the lower Table on p. 323 (Fig. 39) gives the saturated vapour pressure as ·417 in. at that temperature. Ten cubic feet of saturated air at that temperature contains about 47 grains of water vapour.

The pressure remaining the same, a cubic foot of saturated vapour at 54° F. raised to 63·3° F. expands in accordance with Charles's or Dalton's law, being no longer saturated (·002 of its volume per degree), ·019 for the 9·3 degrees. Expanding in the ratio of 100 to 102, the vapour in 10 cubic feet is reduced from 47 to 46 grains.

Now a cubic foot of saturated air at 63° F. contains 64 grs. of water, hence 10 cubic feet of air which only contains 46 grs. are capable of imbibing an additional 18 grs. of water, and this is called the 'Drying Power of the Air.'

The ratio of the density of vapour in the air at 2 p.m. to that of saturated vapour at the temperature is as 46 to 64, or as 71 to 100, *i.e.* the Relative Humidity is 71. (Saturation = 100.)

The conditions at 6 P.M. were significant: the temperature fell slightly and the access of moisture led to rain. This October day presents some unusual features: there was little change of temperature, the morning was warm and very damp; and whereas it is usually the driest time of the day, in this case the air was much drier at 2 P.M.

This is a good instance of the difficulty of predicting weather; there was nothing to suggest at 2 P.M. it would be a wet evening.

One other dew point hygrometer deserves to be described:—

DINES' HYGROMETER.—In this instrument water (cooled by ice if necessary) flows under a very thin piece of blackened glass, and a thermometer is placed with its bulb in the water close under the glass; the flow of water is regulated by a tap. The glass is slowly cooled until dew appears on it; the flow of water is stopped and the temperature of the glass allowed to

rise. The thermometer is read on the appearance and disappearance of the dew; the mean of the readings is the dew point.

Mr. Glaisher expresses the opinion, after his long experience, that the results obtained with the wet and dry bulb thermometers are as much to be relied on as those observed by Daniell's and Regnault's hygrometers. This being so, the advantages of having the instrument always in action and of water alone being required make it far superior to them.

Hygroscopes indicate in a general way the relative humidity or drying power of the air.

Hygroscopes depend for their indications of the presence of water vapour on the behaviour of what are called 'hygroscopic substances.' Fibres, whether vegetable or animal, and some salts absorb moisture. Seaweed, being impregnated with sea-salt, imbibes the moisture of the air and becomes flabby and soft in damp weather; in dry weather it is hard and stiff. A piece of seaweed is often hung up in an entrance hall to serve as a guide to the weather; it tells whether the air is near to or far from the point of saturation and in that way prophesies of rain or fine weather.

When the salt in the salt cellars on the table becomes very moist, it shows that the air is nearly saturated.

When a fibre absorbs moisture it increases in volume; the fibres of twisted catgut swell in a damp atmosphere, so that it untwists. In the old 'weather-house' an arm carrying two figures is suspended by catgut; when the air is damp, the catgut untwists and an old man with his umbrella comes out of his door; when drier, it twists up again and his old wife appears at the other with her parasol.

De Saussure's Hygroscope, an early form, consists of a human hair fastened to a lever moving an index; the hair becomes longer as it imbibes moisture, and shorter as it dries.

Variation in Amount of Vapour in the Air.—The changes in the amount of vapour in the air on a summer's day may be described somewhat as follows. After sunrise the sun's rays pass easily through the dry morning air, heat the ground and

cause evaporation. The temperature rises and the moisture in the air increases until about 9 A.M., when the convection currents from the heated ground begin to carry the vapour upwards, so that though more vapour is formed there is actually less present in the lower layers. A summer day often clouds over for a short time about noon because of the large amount of moisture which rises. About four in the afternoon the rising currents begin to cease, and the vapour in the lower air increases again; and this increase goes on until perhaps nine P.M., when the falling temperature puts an end to further evaporation. In winter what occurs is somewhat different, a maximum density of vapour is reached about two P.M., and a minimum at sunrise. Still, owing to the low temperature at sunrise, the 'relative humidity' is perhaps greater then than at any other time of the day.

Amount of Vapour at different Altitudes.—To secure uniformity at various observing stations it is arranged that thermometers, etc., shall be placed about 4 ft. from the ground. The dew point thus observed shows the vapour pressure at that height. But the change of vapour pressure is very rapid near the ground, and the amount of vapour at a height of 4 ft. may be only one-fourth of that on the surface.

"The vapour decreases gradually as we ascend in the air, there is no increase. Its amount bears the same proportion to its quantity at the sea-level that the saturated vapour pressure at the temperature bears to the saturated pressure at the temperature at the sea-level" (General Strachey, *Phil. Trans.*, 1861).

Modern observations of the upper air by means of kites (p. 360) do not bear this out altogether; but in the main, no doubt, it is true.

Dew.—The natural formation of dew takes place in the same way as the condensation on a cool tumbler or on a hygrometer. At night the earth which has been warmed by the sun loses heat by radiation. The grass and herbage, hairs of wool, etc., radiate heat quickly, and as they stand apart from

the main body of the earth they are not heated by it; so they become very cool, and cooling the air near them below its saturation temperature receive the deposit of water which is called *Dew.*

The formation of dew depends on the moisture of the lower air and the rapidity with which radiation takes place. For example, a clear dry night is favourable to radiation, while moisture obstructs it; a still night permits the cooling of the air, while a wind removes the lower layers before they are cooled, and does not allow sufficient time for the deposit of moisture. Consequently the formation of dew is greatest on a clear and still night, and the deposit varies much on different substances as well as in exposed or shaded positions.

It is not surprising that very varying estimates are made of the amount of dew formed in a year. Dalton estimated it as a layer 5 in. thick, Mr. Dines at 1·5 in. In tropical forests where very warm and damp air is rapidly cooled by the tops of the trees, as they cool rapidly by radiation, dew falls like a shower of rain.

HOAR-FROST is frozen dew; when bodies on which the dew is deposited are below the freezing point, the moisture forms on them in fine crystals, the shapes of which are of extreme beauty.

A GLAZE FROST is one of the most curious of natural phenomena, and it is seldom seen. It seems to be due to the fall of rain which is cooled below the freezing point, but which has not frozen; this possibility has been referred to on p. 343. When the drops touch anything they freeze immediately, so that nature is buried in a shroud of ice.

Clouds.—When the vapour in the air is condensed, not through contact with cold bodies, but through the cooling of a mass of vapour-laden air, then a cloud is formed. A cloud consists of fine droplets of water; if it be near the ground it is called a mist or fog. It would at the outset seem impossible to classify or account for the myriad forms of the clouds, and Professor Ruskin in his *Modern Painters* laments the hopelessness

of the task. But when we come to observe and watch them closely, two main types of cloud-form assert themselves: those which appear in billowy, well-defined shapes, and those which spread over the heavens in a layer, thick or thin, partial or complete.

The former of these is called *Cumulus* (a heap), the latter *Stratus* (a layer); these names are due to Luke Howard (1802), and have been used by all cloud observers since his time. He employed two additional names—*Cirrus* (a curl), to describe the light fleecy forms of the highest clouds, in reality a form of stratus; and *Nimbus* (a rain cloud), to denote the heavy storm-cloud, which is a form of cumulus. Other composite names were interpolated between these,—cirro-stratus, strato-cumulus, etc. No general cloud nomenclature has yet been agreed upon, though a forward step has been taken in the *International Cloud Atlas.* The illustrations are lent by Captain D. Wilson-Barker, of H.M.S. *Worcester.* A sailor has the best opportunities of watching the clouds; and as the wind and weather are of the greatest importance to him, and clouds are the best weather prophets, it is to the sailor rather than to the landsman that we should look for the classification of the clouds. Captain Barker advocates division into the two main types, stratus and cumulus alone, at any rate at first 'as these lend themselves more or less to simple explanation as to their physical formation.'

CUMULUS.—It was remarked (p. 326) that clouds are formed as the moisture evaporated by the sun streams into the upper air. Vapour rises from the earth in convection currents, which are set up as the expanded air rises from the heated soil. Vapour also spreads upwards in the air by diffusion, a slower process, but one which is continually going on. As vapour rises its pressure diminishes and it expands; receiving no access of heat, it cools, thus some of it may condense and take the form of cloud. This '*adiabatic*' expansion of rising columns of water-vapour is the cause of the large class of clouds known by the generic title of Cumulus. Tyndall describes this by saying

that 'the visible cloud forms the capital of an invisible pillar of saturated air.' Besides this cooling by expansion, the upper surface of a vapour column must radiate heat into space, and so cool and condense; this also tends to preserve the form of the cloud by preventing evaporation. Clouds of the cumulus type take many different shapes, of which two illustrations are given — the fine weather cumulus (Fig. 53), taken over the Island of Corvo, and the thunder-cloud (Fig. 54), showing the yacht *Britannia*. Though their shapes vary very much, the

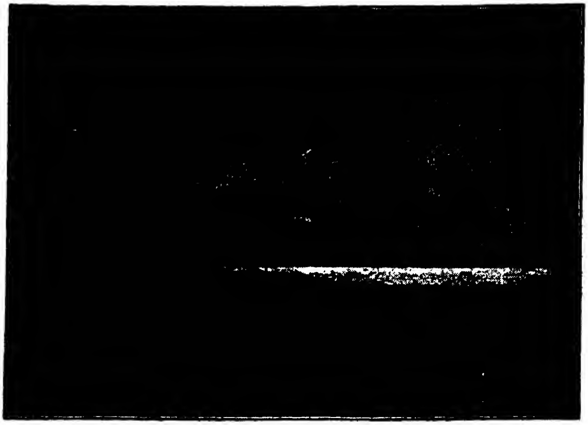


Fig. 53.—Cumulus—fine weather.

type is clearly marked, and cumulus clouds seem to bear their history and origin on their features. They are due to local conditions; streams of vapour rising in one locality are condensed locally, and cumulus appears when the movements of the air are baffling and unsettled.

STRATUS.—Clouds of this type often spread over the heavens like a pall. To draw an east-wind stratus would not require much artistic talent; a patch of gray paper would do very well to represent it. Sometimes, when a cloud of the layer type breaks, the blue sky flecked with bright patches of cirrus is seen through it, and we realise how low and thin this layer

is.[1] On the other hand, these layers are sometimes very high indeed, some cirrus being estimated at 10,000 yards (9000 metres) high.

When south-west winds, laden with moisture, drive up under an upper current of cooler air which condenses part of the vapour, the result is a thick stratus with drenching rain.

Fig. 54.—Cumulus—thunder-cloud.

Observations of the clouds and of the upper atmosphere by means of kites are systematically carried out under the Weather Meteorological Bureau of the United States. This method provides a great deal of useful information bearing on the forma-

[1] "This is a sign of change from settled to unsettled weather; the lower stratus will probably disappear, also at times the cirrus. The sky may be quite clear for some time, then cirrus will be observed forming again in parallel lines, or from a radiant point" (Captain Wilson-Barker).

tion of clouds. Mr. Clayton writes to *Nature* from Blue Hill, summing up the experience of such observations: Stratus is formed by the mingling of a cold lower current with a warmer damp current overflowing it. The stratus is caused by the condensation of the lower plane of the upper current. A thermograph carried by a kite through such a cloud shows a rise of temperature and humidity as the instrument enters and passes through the stratus. This rise of temperature is not shown when the thermograph is lifted into cumulus or nimbus clouds.

Fig. 55.—Stratus— in waves.

We are very familiar with the waves formed in water by the wind blowing over the sea, and can well understand the conclusion of Helmholtz that one current of air blowing over another will raise waves in precisely the same way, though of different dimensions. In certain circumstances the crests or hollows of these waves alone will be condensed as cloud; thus the well-known appearance of a mackerel sky (Fig. 55) will be produced. If now another current pass over these waves in a different direction, forming waves crossing the others, the sky will be covered with a regular network of rhomboid forms,

sometimes of extreme beauty. But such clouds are the certain precursors of stormy weather and heavy gales.

Extremely small portions of these waves may be condensed and so become visible in the wisp-like forms of cirrus; but from what has been said it may be seen that they are really small portions of stratus. They are no doubt composed of ice-needles, and when completely covering the sky cause the halo rings sometimes seen round the moon or sun. The cloud shapes, if watched by an experienced eye, show whether the vapour is condensing or cloud evaporating; fine wisps of cirrus often indicate the beginnings of atmospheric movements, and seem to grow gradually downwards into storm clouds.

Stratus clouds are connected with anti-cyclonic areas, and it has been noticed that they are to be found in the south-western quadrant of the anti-cyclone; the formation of the true stratus is connected with a steady motion of the atmosphere.

It is very different when a rising column of air carries moisture into a cooler current above. Then a nimbus or storm-cumulus is formed and precipitated in rain.

Snow, Hail, and Rain.—When the temperature of a cloud falls below the freezing point its drops freeze and build up the beautiful shapes seen in hoar-frost. In certain circumstances these crystals fall as *snow*. It may be, however, that the cloud is cooled below the freezing point, its drops still remaining liquid, in the manner described under 'Glaze Frost.' Then if a shower falls through it, the drops are instantly frozen, grow to a great size by accretion, and fall as *hail*. Hail never falls *after* it has been raining for some minutes, and a shower of hail never lasts more than about ten minutes; but the amount of ice which falls in that time is sometimes enormous. These facts agree with what has been said as to the probable cause of hail; but it is usually connected with thunder-storms, whether as cause or effect cannot yet be decided.

Rain is formed by the condensation of the water vapour in the air into the form of cloud, and then by the union of the fine drops of the cloud into raindrops. The fine spherules of a mist or cloud

have no tendency to coalesce into larger drops, but rather the reverse. There is a very beautiful experiment described by Professor Boys in *Bubbles* (S.P.C.K.), where small drops of water are shown actually bouncing against one another as elastic spheres, being deformed by the impact and regaining their shape. The magnitude of the surface tension makes them retain their individual existence. It has, however, been shown by Lord Rayleigh that the smallest alteration of the electrical condition in the neighbourhood of a shower of falling drops makes them coalesce (see ELECTRICITY, Fig. 47). Also Lord Kelvin's water-dropping apparatus (Fig. 56) shows how drops of water falling

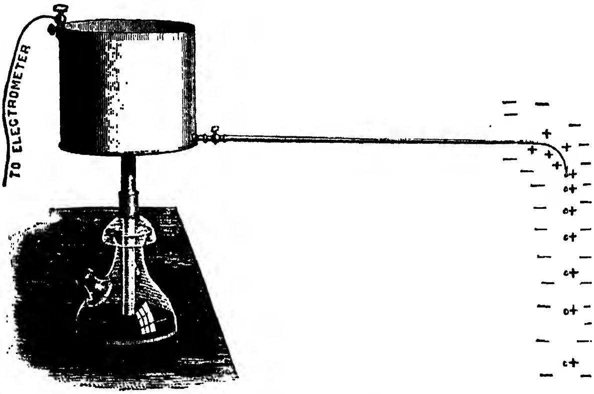


Fig. 56.—Water dropper.

through air are affected by the electrical condition of the atmosphere.

It is a matter of observation that the potential of the air is usually positive; but a change to a negative potential presages a fall of rain, while a change to a positive potential during wet weather is a sure sign that the rain will clear off.

From these facts it is reasonable to conclude that the phenomena of snow, hail, and rain are connected with the electrical conditions of the atmosphere.

A Rain Gauge is used to measure the rainfall in terms of the depth of water falling on a horizontal area. A funnel has

an accurately turned brass rim bounding a circle of known area placed horizontally (Fig. 57). The rain falling into the funnel is caught in a bottle or reservoir and measured in a gauge glass graduated to read in fractions of an inch of depth; the water would fill to that depth a cylinder whose section is the rim of the funnel.

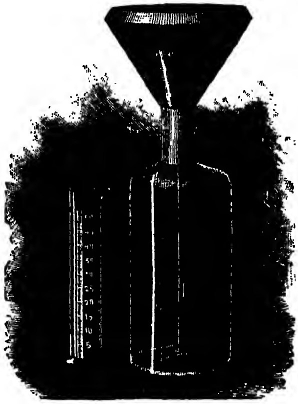


Fig. 57.—Rain gauge.

Rain gauges are made of two sizes, 5 and 8 inches in diameter of rim; they should be placed with the rim about 1 ft. from the ground, and there should be nothing in the neighbourhood at an angle of elevation of more than 20° above the rim, or that would cause eddies in the air.

The rainfall in the British Isles ranges from 20 to 80 inches, being most in the western and least in the eastern part. High land and mountainous districts in the west cause the vapour-laden air from the Gulf Stream to precipitate its moisture before it reaches the eastern part. Exceptional rainfalls occur in such places as the Lake District of Cumberland, 154 inches falling annually at Seathwaite near Scawfell.

Generally speaking, prevailing winds charged with moisture by oceans or warm currents are cooled by the first land they meet, and lose their water there. Hence the large rainfall on the western coasts of India, and of North and South America.[1]

On the other hand, there are rainless regions, such as the Sahara, the steppes of Russia, Gobi or Shamo and the interior of Australia, which are far from oceans—so that the winds that blow across them are dry. As a general rule, the rainfall at places not far from the sea does not differ much from the evaporation. The average rainfall at the Equator is estimated

[1] Peru and Northern Chili form a narrow strip on the western side of the Andes; this range receives on its eastern flank the rain precipitated from the prevalent S.E. Trade Winds, leaving the Pacific coast line very dry.

by Dr. Houghton in his 'Lectures on Physical Geography' at 66·84 inches annually, which nearly agrees with the evaporation there.

Weather Indications.—It is no longer usual to graduate the barometer in the old fashion—Set fair, Fair, Change, as the changes in height rather than the actual height of the mercury column are connected with changes of weather.

The directions given by Admiral FitzRoy for weather forecast from readings of the barometer are as follows:—

ADMIRAL FITZROY'S SPECIAL REMARKS.—In wet weather, if the mercury rise high and remain so, expect continued fine weather in a day or two; if the mercury rises suddenly very high, fine weather will not last long.

The barometer rises highest of all for north and east wind. A rapid rise of the barometer indicates unsettled weather, a slow movement the contrary. A steady rising barometer, when continued, shows very fine weather.

In very hot weather the fall of the mercury denotes thunder, otherwise a sudden fall indicates high wind. In frosty weather the fall of the mercury denotes a thaw. In wet weather, if the barometer falls, expect much wet. In fair weather, if the mercury falls and remains low, expect much wet in two or three days, and probably wind. A sudden fall of the barometer with westerly wind is generally followed by a violent storm N.W., N., or N.E.

If a fall takes place with a rising thermometer, wind and rain may be expected from the south-eastward, southward, or southwestward. A fall with low thermometer foretells snow or rain. A rapid fall indicates wind or wind with rain.

The barometer rises in hard dry weather, because dry air is heavier than damp air, the density of water vapour being about ·6 of that of air at the same pressure and temperature.

The condensation of vapour in the form of cloud diminishes the pressure, because the vapour occupies less space when condensed, and the air expands to take its place.

CHAPTER X

Nature and Sources of Heat

Sources of Heat—Heat a Mode of Motion—Heat a Result of Friction—Heat and Kinetic Energy—Mechanical Equivalent of Heat—Thermodynamics—First Law—Second Law—The Boiler—Combustion of Coal—The Steam-Engine—Expansion—Indicator—Compound Engines.

Sources of Heat.— On the earth, or indeed at all places in the Solar System, the great source of heat is the sun itself. Radiant energy is continually being sent out in all directions from its surface; the mode of transmission is considered elsewhere (Chap. XI. and LIGHT, p. 609). This radiation communicates heat energy to any substance which it meets. The amount of energy radiated by the sun is enormous; it has been estimated that the rate at which energy is given off from every square yard of its surface is 500 horse-power. Pouillet estimates that if all the heat received by the earth from the sun during one year were so employed, it would melt a layer of ice spread over the earth 30 yards in thickness.

Attempts have often been made to drive engines directly by means of the sun's rays. Sun-engines have been built in which the radiation falling on a large area has been concentrated and made to do work. Such machines, however interesting, have never been brought into practical use.

The fuel—wood, coal, and petroleum—used for the production of heat all originate from the sun's action on plant or other growth. The coal measures are due to luxuriant vegetation which flourished on the earth in the early stages of its development.

The earth's own heat no doubt assisted the growth, still in the main the sun's rays must be credited with the energy of vegetable growth.

Combustion is the main source of artificial heat. The process of the combustion of coal is described under the heading of the Steam-Engine (p. 376). Chemical combination is a source of heat in many forms; the combination of the carbon and hydrogen found in coal with oxygen evolves heat.

Heat a Mode of Motion.—Bacon in his *Novum Organum*, lib. ii. cap. xx., says: "From what has been said about Heat, you must understand, not that Heat generates Motion or that Motion generates Heat (though this may sometimes be the case), but that Heat itself or the something which we call Heat is Motion and nothing else."

This is a clear statement of the nature of Heat by one who must be considered as the founder of modern science; it is this statement which Tyndall adopted as a title for his book, *Heat a Mode of Motion.*

Now 'Motion,' as it appears here or in Newton's Laws, is too vague a term for scientific use, and some more exact term must be employed. Experiments shall decide whether Heat is velocity or acceleration, momentum or kinetic energy.

Heat a Result of Friction.—Savages are able to get fire from rapid friction between two pieces of wood rubbed vigorously together. Few lecturers would be able to show this to a class; Prof. Tyndall introduced an experiment which makes less demand on the muscles.

On the axis of a whirling table (Fig. 58) a brass tube is screwed so as to rotate, being vertical. This is half filled with water and corked. Two hinged boards are arranged to grip the tube and hold it in a groove which is lined with leather. When the tube is rotated rapidly and pressure applied to the boards, the tube is heated, the water boils, and finally the cork is driven out, as shown in the figure.

Here Heat appears as associated with Motion. If it be asked what sort of visible motion has been exchanged into the invisible

motion which we call Heat; it is not momentum. There may have been no change in the momentum of the apparatus; yet there has been a gradual development of Heat. What then has been done? *Work has been done* on the handle of the whirling table which has been pressed with a definite force through a definite distance.

The 'Principle of Work' applies only to 'perfect' machines. In a real machine some work is done against friction, so that

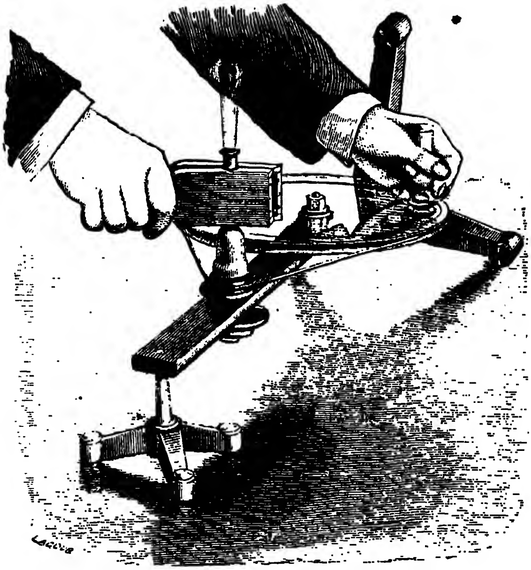


Fig. 58.—Friction and heat.

in practice the work done *on* a machine is not equal to the work done *by* the machine. The work done against friction produces kinetic energy in the form of heat.

Heat and Kinetic Energy.—A metal plunger fits well in a strong metal cylinder, at the bottom of which is placed a piece of tinder. Now if the plunger be put in the cylinder so as to enclose some air, and then be smartly pushed in, or better still, hammered in smartly with a heavy hammer, the air inside

becomes intensely hot, and the tinder may be shaken out of the tube glowing.

Here the 'motion' of the hammer has been arrested and heat has been produced; it is kinetic energy which has been exchanged into heat; in the former experiment, work done produced heat. But work done and kinetic energy are convertible terms (MECHANICS, p. 40), so that if Heat be 'Motion' it must be a kinetic energy (see PROPERTIES, p. 119).

When we see what is called a 'falling star,' it is intense heat which has rendered it visible. A 'siderite' or piece of planetary stone has plunged into the envelope of air surrounding the earth with great relative velocity. The friction between the air and the stone does work and diminishes the kinetic energy of the stone, and heat is produced.

Now if heat is produced by work done or by loss of kinetic energy, it should be possible to find a numerical value in units of heat which shall correspond to work done or kinetic energy in foot-pounds.

Mechanical Equivalent of Heat.—The experiments of Dr. Joule of Manchester (1843-49) established a numerical relation between a thermal unit and a foot-pound.

These experiments were of three kinds, the first of which is the best known.

1. A known quantity of water was placed in a vessel like a churn, and heated by being dashed about by moving paddles. The work done against the resistance of the water being measured, and the rise of temperature of the water observed, the number of foot-pounds corresponding to a thermal unit was calculated.

In the original apparatus, the churn or calorimeter (Fig. 59) had vanes or breakwaters V, V, and the paddles P, P were carried on a vertical axis. The suspended weights caused a tension W, W in cords passing round the calorimeter, which was free to revolve about C. If the paddles had been fixed, the work done on the water might have been measured by the product of 2W lbs., the number of revolutions of the calorimeter

and its perimeter in feet. Instead of this, the axis and paddles were rotated at such a rate that the weights remained steady, being supported by the friction of the paddles; the work done was measured by substituting the number of revolutions of the axis for that of the calorimeter.

2. The heat produced by the friction between two metal surfaces was employed in heating water. The work done against friction was measured, and the rise in temperature of a known mass of water ascertained, from which Joule calculated the Mechanical Equivalent.

3. Air compressed by a pressure of 20 atmospheres was allowed to expand, thus doing work against a known pressure and cooling in consequence. In this as well as in the other

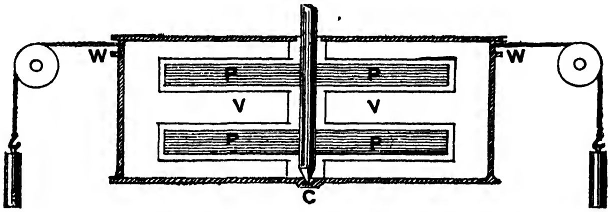


Fig. 59.—Joule's apparatus.

experiments, the heat was communicated to water and every precaution was taken in devising the apparatus and carrying out the experiments to avoid the access or loss of any heat owing to surrounding objects.

Joule concluded that one British unit of heat corresponds to 772·7 ft.-lbs. of work. Since the experiments of Joule, Profs. Griffiths and Schuster (1894) undertook, independently of one another, a calculation of the mechanical equivalent. The work done by an electric current in heating a wire can be measured in foot-pounds, and if it be employed in heating water the corresponding number of thermal units is found. By this method they arrived at a value of J, 780·2 (*Griffiths*) and 779·7 (*Schuster*) foot-pounds at Greenwich at 15° C., referred to the 'Paris' nitrogen thermometer.

The thermometers used by Joule were entrusted to Prof. Schuster for comparison with modern thermometers, and making the necessary corrections he concluded that the value given by Joule's experiments is 775 in the above conditions. Two other serious determinations have been made — that by Rowland, 778·3, and that by Miculescu, 776·6, in the same conditions.

These experiments and calculations have substituted 778 (ft.-lb. Fahr.) or 4·19 Joules (10^7 ergs) per gramme centigrade unit of heat as the value of J, '*The Mechanical Equivalent.*'

Experiments such as those of Joule, Griffiths and others are often referred to as determining the *Specific Heat of Water*, as that is the physical constant which is involved. A unit of work is an absolute quantity; the unit of heat depends on the characteristics of water; if another liquid were employed the numerical value of J would be different.

Thermodynamics.—The science of the conversion of mechanical energy into heat or the converse is called *Thermodynamics.* A heat-engine is a machine in which heat, usually caused by combustion, produces mechanical energy and takes the place of the work done on the machine.

The principle of the conservation of energy (MECHANICS, p. 41), when extended to heat, is expressed in what is known as **The First Law of Thermodynamics.**—*A definite quantity of heat is called into existence by every unit of work done without producing mechanical energy; and conversely, when mechanical energy is produced from heat, a definite quantity of heat goes out of existence for every unit of work done.*

The connection between the amount of heat called into existence by work done and kinetic energy has been shown to be :—

One unit of heat can be produced by the expenditure of 778 ft.-lbs. of work. It is natural to inquire whether this can be reversed; in other words, Is it possible to convert one unit of heat into 778 ft.-lbs. of work? The answer to this question depends on the axiom which, under one form or another, is the **Second Law (Clausius)**:—*Heat cannot of itself pass from a body at a lower to one at a higher temperature.* 'It is impossible by

means of inanimate material agency to derive mechanical effort from any portion of matter by cooling it below the temperature of the coldest of the surrounding objects' (Kelvin). Temperature is the test of the availability of heat for doing work.

It follows that in the working of any engine 'heat will be lost,' not because it disappears, but because it is at a temperature too low to be available. For a complete discussion of the conversion of heat into work the student must be referred to works on Thermodynamics; a slight account of the steam-engine alone is possible here.

For about 200 years steam has been used as the substance by which heat is converted into work. Progress has been made from Savery's small and very wasteful pump to the powerful engines of modern steam-ships with their 'economical' working. In these, the consumption of coal has been reduced to $1\frac{1}{2}$ lb. per horse-power hour instead of the $2\frac{1}{2}$ lbs. of 25 years ago. Now the combustion of each pound of Welsh coal gives 15,235 thermal units, equivalent to about 5000 foot-tons of work. According to this, one horse-power hour is the mechanical equivalent of the heat in $\frac{1}{6}$ lb. of coal, which is barely $\frac{1}{10}$ of the coal required. From this it may be seen how far our most economical engines fall short of converting all the heat into work. In describing the conversion of heat into work in a steam-engine, it will be well to note at what points heat is 'lost,' *i.e.* allowed to escape without doing work.

The Boiler consists of two main parts,—the shell in which the water is contained, and the heating surface by which heat is communicated to the water. In the older types of marine boiler, and in the boilers of railway locomotives the furnaces and heating surfaces generally are wholly contained inside the shell. In the newer forms of boiler, known as 'tubulous' or 'water-tube' boilers, the water is contained in tubes entirely surrounded by the furnace.

The *Low* or *Through Tube Marine* boiler, illustrated in Fig. 60, is a very good type of boiler for simple discussion, because it is easy to distinguish its parts. It is a boiler suitable

for use in a steam-vessel with a small draught of water, as it is low and long. The fuel is burned on the grate bars L,L, and, the smoke and heated gases mixing with air, the com-

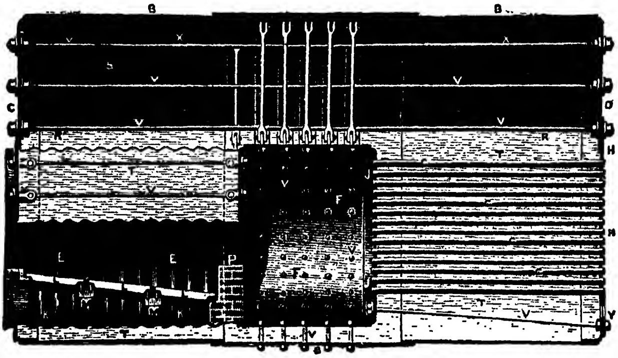
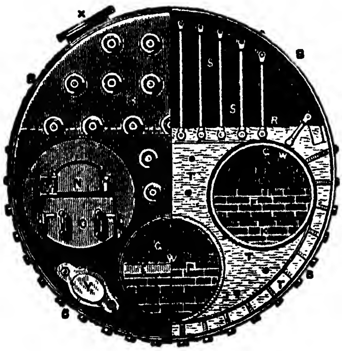


Fig. 60.—Low marine boiler—Section.



Front view.

In these figures—

B represents the *shell.*
C *Front* of boiler.
D *Back.*
E *Furnaces.*
F *Combustion chamber.*
G *Tubes.*
H *Back tube plate.*
J *Front tube plate.*
K *Ashpit.*
L *Furnace bars.*
M *Bearing bars.*
N *Furnace door.*
O *Ashpit door* or *draught plate.*
P *Bridge.*
R *Water line.*
S *Steam space.*
T *Water space.*
V *Stays.*
W *Stay tubes.*
X *Man-holes.*
Y *Mud-holes.*

bustion is completed in the combustion chamber F. In the locomotive boiler the furnace and combustion chamber are combined in a cubical box, sometimes of copper, the ashpit opening to the air; the fire-box end of the boiler is made square to hold

it. In the earlier locomotives, the value of a combustion chamber was not appreciated, and in consequence, when coal was used, there was great difficulty with the heavy cloud of smoke which was not properly burned. Hence coke was used at a considerable cost. Of late years the fire-box has been divided by a brick arch, so that its upper part forms a combustion chamber, and coal is used.

Water-tube boilers are those in which the heat required to raise steam from water is applied to the *outside* of the tubes, the water being inside; they possess several advantages over the older forms of marine boilers.

The *Belleville* boiler, illustrated in Fig. 61, consists of several sets of tubes placed side by side over the fire, and enclosed in a casing formed of non-conducting material. Each set of tubes, called an *element*, is constructed in the form of a flattened spiral, and consists of a number of straight tubes A, B, C, D, etc., screwed at the ends and connected to *junction boxes* E, F; the junction boxes at both ends of the elements are placed vertically over each other and are so constructed that the upper end of one tube is on the same level as the lower end of the next tube in the spiral. The junction boxes E are closed at the ends, but those marked F at the front end of the boiler are fitted with small doors, so that the interior of each tube may be readily inspected.

The lower front box of each element is connected to a horizontal cross tube at the front of the boiler, called the *feed collecting tube* H, and the front upper box is connected to the bottom of the *steam receiver* G, which is a horizontal cylinder running along the front of the boiler above the casing.

The furnace bars J, and furnaces T, with fire-brick sides and back, are arranged under the elements as shown in sketch; the hot gases pass up between the tubes to the uptake R and funnel. Furnace doors K and draught plates L are fitted as in ordinary boilers. The smoke-box doors M are arranged over the ends of the tubes at the front of the boiler, these can be removed when necessary to clean or examine the tubes, and are opened for the purpose of checking the combustion and consequent generation of

steam when necessary. Ashes falling through the furnace bars are collected in the ashpans S.

In order to secure complete combustion in the furnaces before the gases rise between the tubes, jets of air under pressure are delivered from a pipe led along the front of the boiler above the furnace doors; the amount of air admitted through this pipe may be varied as necessary to suit the rate of combustion or the kind of coal used. Baffle plates, as shown at V, are fitted horizontally between the tubes, to ensure the thorough circulation of the hot gases around them.

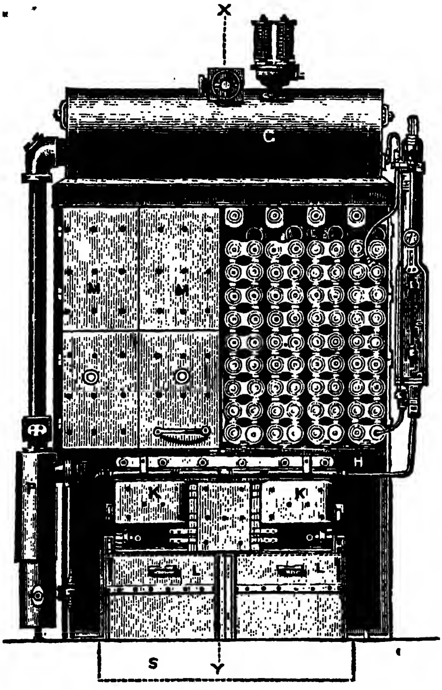


Fig. 61.—Belleville boiler—Sectional elevation.

When the boiler is in use, the water level N is at about half the height of the elements; water is supplied at the bottom of each element, is partially evaporated in the lower tube and passes partly as steam and partly as water through the back junction box into the next tube, where a further portion is evaporated, and so on. Each tube has, therefore, to convey all the steam formed in the tubes of the same element which are below it as well as the steam formed within itself. A mixture of steam and water is thus continuously discharged from each element into the receiver G.

The water from the feed pumps is admitted to one end of this

receiver, where it mixes with the water from the tubes, passes with it to the other end of the receiver, thence by an outside circulating pipe to the collecting tube, and so to the bottoms of the elements. An arrangement is made by means of a *sediment chamber* P in connection with the pipe leading from the steam receiver to the elements, to separate impurities from the boiler water; from this they can be blown overboard as necessary. Self-regulating feed supply arrangements are provided for these boilers to keep the water at the proper height. The steam receiver is fitted with the usual stop- and safety-valves, pressure-gauges, etc. the water-gauge is shown at N.

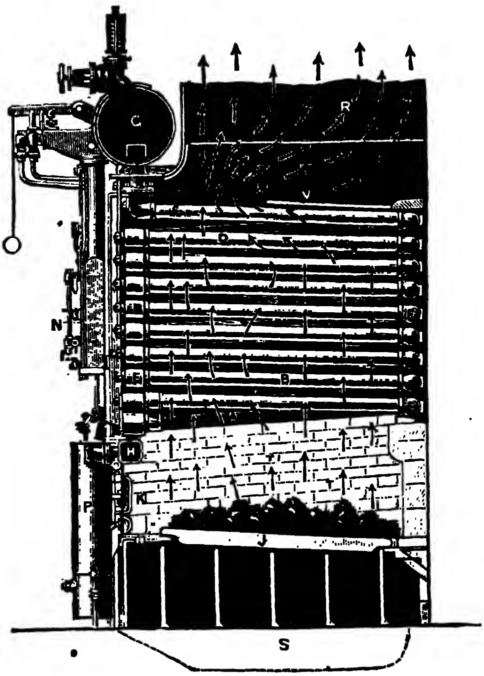


Fig. 61.—Belleville boiler—Section through XY.

As a very small amount of water is used in these boilers compared to that in the ordinary boilers there is more fluctuation in the pressure of steam, and arrangements are made to keep the pressure supplied to the engines constant. This is done by keeping the pressure of steam in the boilers above that required for the engines, the supply to which is regulated by an automatic reducing-valve (not shown in sketch) so constructed that a constant pressure reaches the engines, however much the pressure in the boilers may vary. If the pressure in the boilers should

fall below that at which the reducing-valve is set, it would open fully and allow the whole of the boiler pressure to pass to the engines.

The advantages claimed for water-tube boilers over the ordinary marine types are :—

1. That they may be safely worked at much higher pressures than cylindrical boilers, and so greater economy can be secured.

2. They are much lighter than the cylindrical boiler of the same power, both being worked under the same conditions of natural draught.

3. They are much more easily repaired or replaced than ordinary boilers. A damaged element of a Belleville boiler can be replaced by a spare one in a few hours, while a whole set of boilers could be replaced without cutting up decks, etc., as necessary for ordinary boilers.

4. In the event of accident to, or fracture of any part of a water-tube boiler, there would be much less risk either to life or the ship because of the small amount of water used. The amount of water at working height in one of H.M.S. *Terrible's* boilers is little over one ton, while in an ordinary return-tube boiler the amount of water is over twenty tons.

In considering the steam-engine as to its conversion of the heat of burning coal into work, it is necessary first to consider combustion itself.

Combustion of Coal.—*Combustion is a rapid chemical combination of the oxygen of the air with the hydrogen and carbon of the coal, light and heat being evolved.*

There are two stages in the combustion of coal.

I. When coal is first thrown on the fire, it absorbs heat, and the hydrocarbons are driven off: if sufficient air be mixed with them, and the temperature of the mixture of the air with the gases is high enough, these are burnt in the furnace and combustion chamber. If not, they go off in the form of smoke, and the heat which would be evolved by their combustion is lost.

II. The solid portion of the coal, the carbon or coke, then remains to be burnt. The air required for this passes through

the spaces between the furnace bars, the supply into the ashpits being regulated by the draught plates.

If sufficient air is supplied, the combustion of the coke is complete, and the product of combustion, *carbonic acid gas* or *carbon dioxide*, passes away into the uptake and funnel.

But if the supply of air is insufficient, or the fire is thick, the *carbonic acid* CO_2 loses one part of oxygen in combination with the glowing carbon, and passes from the fire in the form of *carbonic oxide* CO. As this gas will burn and give out heat by combination with additional oxygen, it would be a waste of heat to allow it to pass unconsumed into the funnel. The air which passes through the gratings in the furnace doors affords oxygen for the combustion of this gas, as well as of the hydrocarbons in the combustion chamber.

To effect the complete combustion of 1 lb. of coal 12 lbs. of air are necessary, theoretically.

In practice this has to be exceeded, as the products of combustion require to be diluted if combustion is to be complete; with *artificial draught* about 18 lbs. are desirable, and with *natural draught* (that is draught due to the height of the funnel or chimney alone) about 24 lbs. This would occupy a volume 16,000 times as great as that of 1 lb. of coal.

Supply of air—Natural draught.—In ordinary cases this supply of air is kept up by the *natural draught*. The heated gases in the uptake and funnel being lighter than the air outside, ascend, and to supply their place fresh air is drawn through the furnaces. About one-fourth the heat produced in the furnaces is expended in this way; the temperature of the gases in the funnel is about 600° F., and in the furnaces about 2400° F.

From this description it may be seen that waste of heat occurs in several ways.

1. The gases first driven off escape in the form of smoke, which is unconsumed carbon.

2. Some carbonic oxide escapes unconsumed.

3. Some carbon is thrown away with the ashes.

In these three cases, heat accounted for in the theoretical

value is actually not evolved, the combustion having been imperfect. Besides this,

4. Heat which finally escapes from the funnel is lost.

5. Heat is lost by radiation from the heated surfaces.

As to the escape of heat from the funnel, the fall of temperature from 2400° F. in the furnace to 600° F. in the escaping gases is alone available for making steam; the fall from 600° F. to the 60° F. or so of the atmosphere is 'lost.'

The difference between the '**available**' evaporative power and the **theoretical** available power is due mainly to the following causes: (1) Waste of unburnt fuel in the solid state. (2) Waste of unburnt fuel in the smoky or gaseous state. (3) Waste by external radiation and conduction. (4) Waste or loss of heat by the escape of hot gases.

The Steam-Engine.—The steam having been raised is admitted to a cylinder in which it does work in forcing a piston from end to end of the cylinder. The steam is admitted, first to one end of the cylinder, and then, while this is allowed to escape, fresh steam is admitted to the other end to force the piston back. The student may understand this better with the aid of the movable diagram (Fig. 62) which is here introduced; the piston rod E can be moved with one hand, while the rod L, which moves the slide valve K, is moved with the other. Place the piston BCD at the top of the cylinder A; the slide-valve K should then be placed in the middle of its travel. The space J in which the slide-valve is moving is called the valve chest or *slide-jacket*, and is full of steam from the boiler. M is the hollow of the slide-valve, like the hollow of the hand, covering the holes or 'ports' F, F which lead into the cylinder. The slide-valve should now be moved slowly down; the steam will rush from J through F into the cylinder and force the piston down. At the same time the steam which is in the lower end of the cylinder finds a way open to it through the hollow M to the exhaust-pipe H, by which the steam escapes. By the time the piston has got half-way down, the slide-valve K should reach the end of its travel, and begin to move up; it

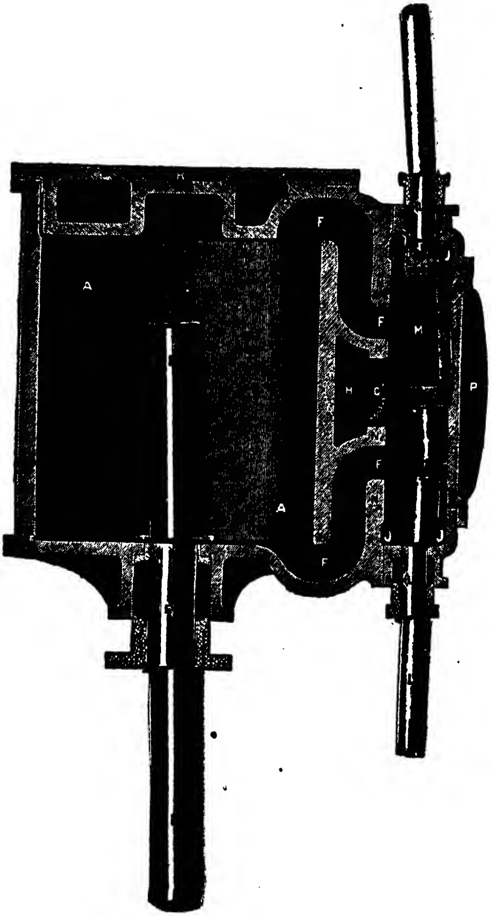


Fig 62.—Sketch of section of cylinder, with movable piston and slide valve.

closes the upper cylinder port F, so that no more steam enters there, and the steam in the upper part of the cylinder expanding still forces the piston down until it reaches the bottom. By this time the slide-rod is in the middle again, and the operation repeats itself for the return stroke. The left hand raises the piston-rod E and the right hand continues the upward motion of the slide-rod L; the steam may be supposed to pass from the slide-jacket J, through the lower port F to the cylinder, forcing the piston up, while the steam from the upper part of the cylinder escapes through the upper port to the exhaust H.

This description has been given to explain to the student how the steam is led to force the piston of a steam-engine backwards and forwards. The mechanism by which the motions of the slide-valve and piston are regulated and the way in which the work is done by the piston-rod can be found in a practical book, such as *Steam and Steam Machinery*, Langmaid and Gaisford, Macmillan, from which these diagrams are taken.

Expansion.—The slide-valve cuts off the supply of steam to the cylinder at a certain part of the stroke, and the steam expands through the remainder of the stroke. This is called working expansively, and its effect on the economical working of the engine must be considered.

In the early steam-engines the steam was produced at a low pressure, 2 or 3 atmospheres (sometimes indeed at little more than atmospheric pressure), and a cylinder full of steam at this pressure was used in each stroke. In a condensing engine the steam is then led away into a condenser, and so the whole pressure was effective to do work. In non-condensing or 'high-pressure' engines the steam is allowed to escape into the air; in these there is at least one atmosphere of back pressure.

In any case, the steam in the cylinder does work in pressing the piston, and one unit of heat disappears for every 778 foot-pounds exerted, being cooled to that extent and partially condensed. This is all the heat that is utilised, and the rest of the heat, both sensible and latent, in that cylinder full of steam is lost so far as work is concerned.

In the diagram (Fig. 63) the vertical lines AC, XS, YT represent pressures of steam which fill a cylinder, whose volume is represented by the horizontal lines AX, AY, by forcing a piston to a distance which may also be represented by AX, AY. The complete diagram, giving the pressure, specific volume and latent heat, etc. of steam at various temperatures is repeated (Fig. 64) to assist the reader in studying numerical examples.

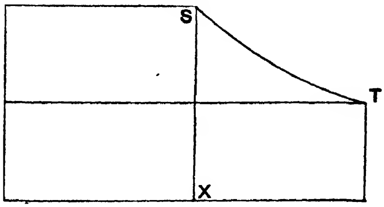


Fig. 63.—Expansion of steam.

Suppose that 1 lb. of steam at 5 atmos. pressure fills a cylinder represented in volume by the line AY (5·68 cub. ft.), the force exerted on the piston is the product of its area and the pressure of the steam; the piston area being constant, this force is also represented by the line AB. Since the line AY represents the stroke or distance through which the piston is moved, the work done by the steam is represented by the rectangular area AT. Suppose that 1 lb. of steam at 10 atmos. pressure is admitted to the same cylinder, its volume (2·96 cub. ft.) being represented by AX, the steam forces the piston through a distance also represented by AX, and does work represented by AS.

But this is not all the work which this steam can do, for it can expand and fill the cylinder, forcing the piston to Y with a continually decreasing pressure, represented by the ordinates decreasing from XS to YT. When it has filled the cylinder the steam at 10 atmos. has done work represented by the area of the irregular figure ACSTYX,—more work than is done by the steam at 5 atmos., as the irregular figure AS is greater than the rectangle AT.

The total heat of steam at a pressure of 5 atmos. is 1175 F. units, and at a pressure of 10 atmos. 1190. Hence a pound of water can be converted into steam at 10 atmos. by expending only 15 more F. thermal units than are necessary to produce steam at 5 atmos.

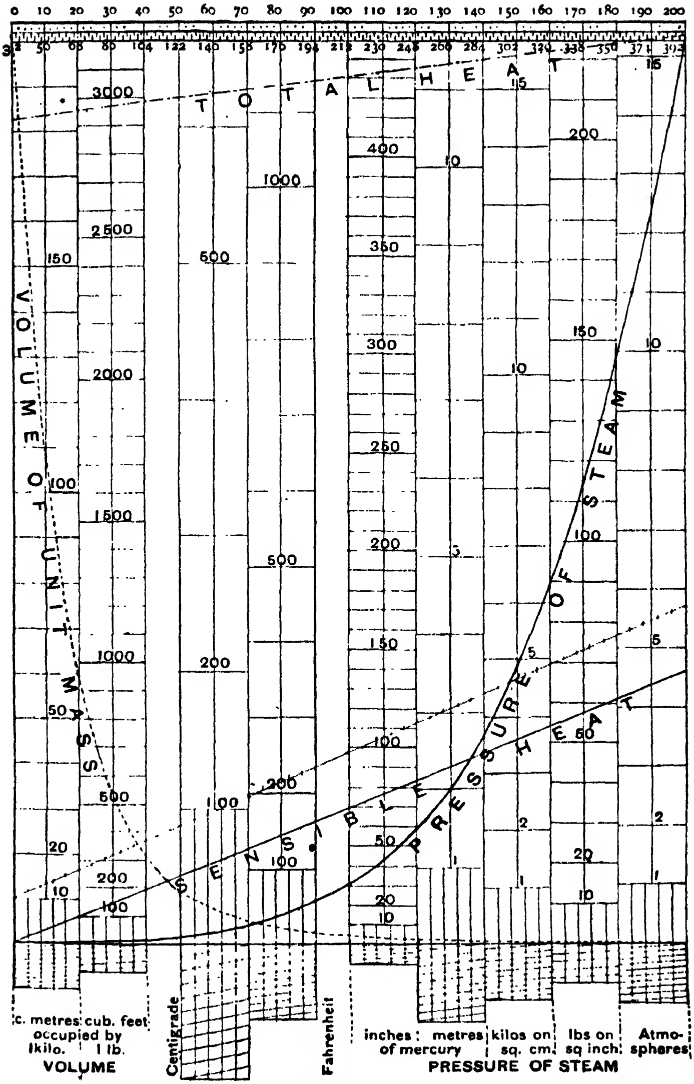


Fig. 64.—Total and latent heat.

The Indicator records the work done in a cylinder by a diagram such as that given above. So long as the indicator cock D is open, the steam cylinder is in direct communication with the indicator cylinder. The small piston P (Fig. 65) is moved up and down by the varying pressure in the cylinder balanced

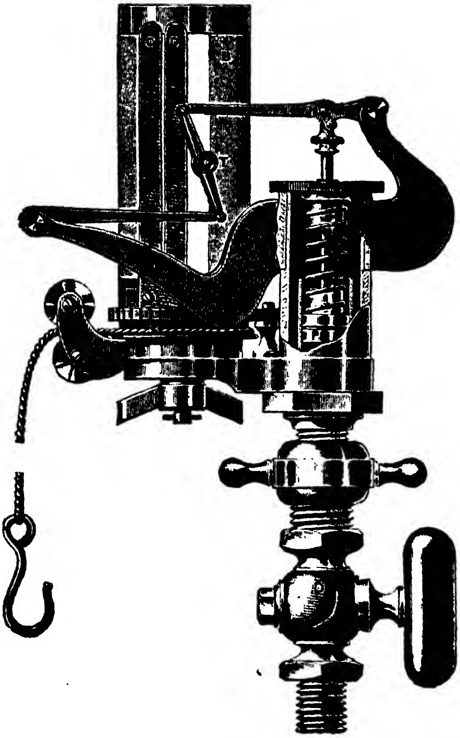


Fig. 65.—The indicator.

by a spiral spring. Paper is fastened to the barrel B by clips C, and the pencil T makes a vertical line on it as the pressure varies. The barrel is pulled by the string S, which is led to some lever worked by the piston rod—a coiled spring in the barrel pulling it back. This gives an oscillating motion to the paper, so that the pencil, if still, describes a horizontal line on the

paper. When the pencil is moving with the varying pressure and the paper oscillating with the motion of the piston, a curve is described somewhat similar to the theoretical diagram (Fig. 63).

When a diagram has been taken the indicator cock D is closed, and the pencil describes a horizontal line of no pressure, 'the atmospheric line BF.' The diagram then appears as shown in Fig. 66. ABCD is the admission of steam, DEFG the expansion reducing the pressure, GHA the 'vacuum' when the pressure at the back of the returning piston is less than the atmospheric pressure.

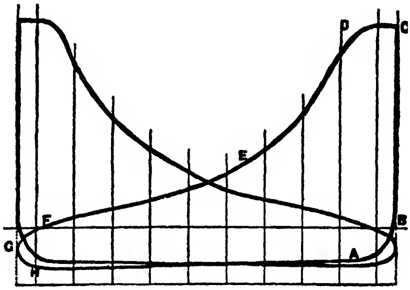


Fig. 66.—Indicator diagram.

The numerical value of the vertical lines in lbs. per sq. in. are given for each spring by the makers and checked by experience, the horizontal travel of the pencil corresponds to the 'stroke,' and the work done in the cylinder is calculated from the area of the diagram.

It is not within the scope of this work to discuss practical indicator diagrams. What has been said is sufficient to show how the work done by the steam is measured.

Compound Engines.—The economy effected by using high pressures of steam subsequently expanded, will evidently be increased by using higher pressures in the boiler, and by expanding the steam so much in the cylinder that the pressure falls nearly or quite down to the pressure in the condenser. It is, however, very trying to an engine to have such great variations of pressure on the piston. If the pressure be so much varied, a great strain is put on the piston rod and other parts of the machinery. It is also wasteful to have large variations of temperature during the stroke, as the incoming steam is cooled by the cylinder in that case and partly condensed during

admission. It is therefore usual to carry out the expansion of the steam in two, three or even four cylinders into which it goes successively; engines with high- and low- pressure cylinders are called compound, those with three or four successive cylinders triple or quadruple expansion engines. Thus economical working has been much increased, the use of steel in the construction of boilers having rendered it practicable to use very high pressures. But even if further improvements are made, the steam-engine will still be unable to convert more than a small fraction of the heat of combustion into work. The more the temperatures differ at which heat is taken in (at the boiler) and rejected (at the condenser) the greater is the fraction which may be turned into work: it is an advantage for this difference to be as low in the scale of temperature as possible (Second Law of Thermodynamics).

A gas-engine or a hot-air engine is theoretically capable of turning a large fraction of its heat into work, because in it the working substance passes through a wider range of temperature than does the steam in a steam-engine.

Steam Turbines are being increasingly used in steam-ships and for electric generators. In these, vanes are placed diagonally on the cylindrical steps of a drum which increases by steps. The drum runs in a casing also increasing by steps, and guides, fixed to the inside of the casing, direct the steam on to the vanes. The general direction of the steam is parallel to the axis of the drum, entering at the smaller end of the casing and expanding at each set of vanes.

Large steam turbines have a high efficiency, and are as economical as the best reciprocating engines: the steam expands from 250 or 300 lbs. per sq. in. to vacuum, and there is little loss from friction and none from change of momentum in working parts.

For further treatment of the theory of the steam-engine, the reader is referred to *The Steam-Engine and other Heat Engines*, by Professor Ewing, Pitt Press.

The short sketch of the steam-engine given here owes its value entirely to the assistance which Professor Ewing has generously afforded, and to the text-book of J. Langmaid and H. Gaisford, Engineer Officers, R.N.

CHAPTER XI

Transmission of Heat—Radiation

Radiant Energy—Rectilinear Propagation—Intensity of Radiation—Reflection—Refraction—Diathermancy: of Solids, of Liquids, of Gases, of Water Vapour—Obscure Rays—Greenhouses—Absorption—Radiation and Absorption—Radiation from Surfaces—Absorption at Surfaces—Radiation and Absorption Compared—Reflecting Power—Distribution of Radiant Energy—Cooling—Rate of Cooling—Prevost's Law of Exchanges—Mobile Equilibrium of Temperature.

Radiant Energy.—The heat of the sun's rays and the pleasant warmth of an open fire when those rays fail in their generosity both illustrate the Transmission of Heat to a distance by Radiation. The sun is a source of heat as well as of light; its rays passing over the millions of intervening miles affect our sense of feeling as well as of sight. Some light rays, such as moonlight, impart no perceptible heat; some heat rays, such as the radiation from a boiler or steam-pipe, can be plainly felt at a distance though no rays can be seen. Yet there is no doubt that both are conveyed in the same way. *Radiation is the transmission of heat from a hotter to a colder body by means of vibrations of the luminiferous ether.* The subjects of light and heat overlap at this point, the laws of transmission of radiant heat being the same as those of light, and the manner of transmission also.

Radiation is sometimes defined as the transmission of heat energy through a medium without heating it. This is incorrect, unless by 'medium' is meant the ether whose vibrations transmit the energy. The term 'medium' is usually applied to the

intervening substance — gas, vapour, liquid or solid, which is always heated more or less by radiation through it.

In conduction, heat passes at any point from a hotter particle to its cooler neighbour, but in radiation the temperature of the intervening substance does not come into the question.

At the surface of the radiating body heat-energy is transformed into energy of vibration of the luminiferous ether, which is again transformed into light or heat on meeting some other body, but which on the way is not what is ordinarily known as light or heat.

When treating of light, it is in place to point out (LIGHT, p. 602) that from a source of light there proceed also rays which do not cause light, but which produce heating effects.

Such rays are called by Tyndall 'obscure' rays, and to detect them and measure their intensity the thermopile is used, with its 'spot of light' as an index. This instrument is referred to on p. 262 and fully described in ELECTRICITY, Chap. VIII.; it was brought into use by Melloni, whose researches on radiant heat will often be referred to.

Rectilinear Propagation.—An upright stand is provided on which a heated iron ball may be placed; also a double heat screen, which has a square hole through it; a plain screen is placed at an equal distance on the other side. Now if a candle be placed on the stand, so that its flame occupies the position which the ball will occupy, a square of light is traced on the plain screen, showing that the rays of light proceed in straight lines through the hole. The ball is heated and placed on the stand; the eye can no longer detect any rays, but if a thermopile be brought to the place where the square of light was seen on the plain screen (Fig. 67), the 'spot of light' is instantly deflected, while at other places there is little effect on the thermopile. This shows that the 'obscure' heat rays as well as the light rays proceed in straight lines.

A 'double screen' is used in experiments on heat to intercept radiation. It consists of two parallel sheets or plates of tin or wood standing vertically, with a space between them for the cir-

culation of air. The plate nearer to the source of heat may become heated, but the convection currents passing up between the two plates carry away the heat and prevent any heating of the further plate. This does not, therefore, receive any of the radiant heat from the source, and the radiation is entirely intercepted.

Intensity of Radiation.—Every one knows by experience that the intensity of radiant heat diminishes with the distance from the source, for if you find it too hot near the fire you must move further off. If it be asked, What is the law of diminution? the experiment last conducted (Fig. 67) may make it clear. Suppose that the hole in the double screen be exactly one inch square, and this screen be placed half-way between the

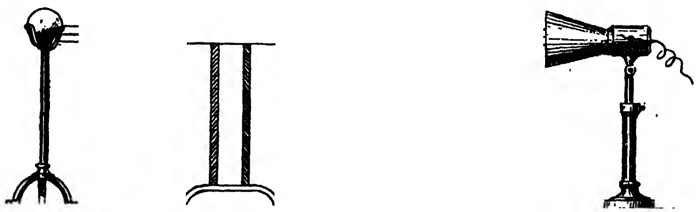


Fig. 67.—Rectilinear transmission.

further screen and a candle. The patch of light on the further screen is exactly four square inches, *i.e.* four times the area of the hole. The energy passing the square inch at the hole has, in double the distance, spread itself over the four square inches. And it was shown in the last experiment that radiant heat as well as light is transmitted in straight lines.

An experiment which was devised by Melloni illustrates the law of transmission of 'obscure' heat. A large flat-sided tin box is filled with hot water, and a thermopile is placed with its cone collector in front of the vertical flat surface of the box (Fig. 68),—the spot of light is at once deflected. Now remove the thermopile further from the box, or approach it nearer, the spot of light does not move, showing that the

intensity of radiation falling on the thermopile does not change.

The cone collector limits the rays received by the thermopile to those proceeding from a circle in which the cone cuts the surface of the box, as is indicated by the dotted lines in the figure. When the cone is approached to the box this circle is diminished, and when it is removed the circle is increased.

The area of the circle from which rays are received varies as the square of the distance of the thermopile. As the spot of light shows that the total intensity of heat received by the thermopile does not vary, it follows that the intensity of the radia-

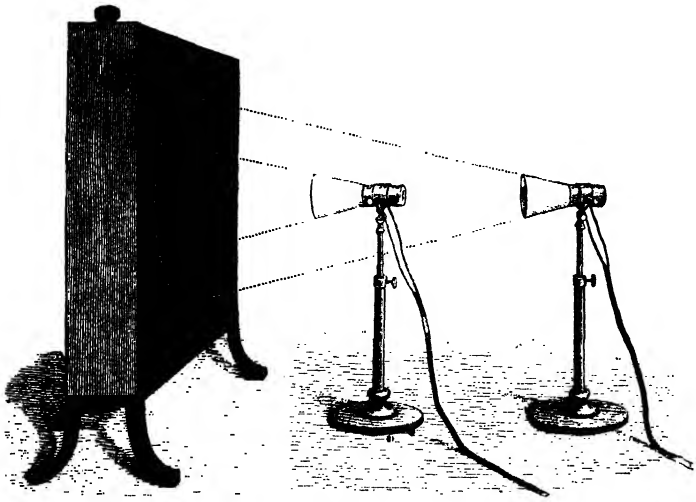


Fig. 68.—Melloni's proof.

tion from a source of heat varies inversely as the square of the distance from it.

If it be understood that radiation is a wave motion, then the proof which is given in WAVE MOTION (p. 445), for the general case (intensity of spherical waves) applies here.

Reflection.—When roasting meat before an open fire it is

usual to place a bright tin screen round it to reflect the rays of heat back on to the joint.

The apparatus used to illustrate the reflection of light (p. 404, and LIGHT, p. 519) illustrates the reflection of heat. A thermopile is placed opposite the openings and a source of heat is substituted for a candle. In another experiment two large concave mirrors of polished metal are fastened to supports, so that their axes are horizontal and coincident (Fig. 69). If a lighted candle be placed at the focus of one of the mirrors, that is half-way between its centre and its surface, the light is reflected and thrown in nearly parallel rays to the other mirror. There the rays are reflected, and converge to the focus of

Fig. 69.—Reflection.

that mirror. This can be seen by the large amount of light making an image of the candle flame, which is thrown on a piece of paper placed there.

If a flask of hot water or a heated ball be substituted for the candle, and a thermopile for the piece of paper, the rays of heat are shown to be reflected in exactly the same way as the rays of light. The spot of light flies rapidly to one side when the thermopile is placed at the focus of the mirror and turned towards it, though when turned in the opposite direction it shows no movement due to the direct rays from the source of heat.

It is plain from these experiments that the laws of the radiation of heat are the same as those of the radiation of light.

Rectilinear propagation, the law of inverse squares and the law of reflection are the same with both.

Refraction.—Few boys have not burned holes in their clothes or done other mischief with a 'burning glass.' The sun's rays are concentrated by refraction through the lens, and their intensity at a point is so much increased that cloth or paper is charred. Campbell's Sunshine Recorder consists of a glass ball (Fig. 70) which concentrates the sun's rays on a card-

Fig. 70.—Campbell's sunshine recorder.

board cylinder, on which the principal focus of the sphere falls. So long as the sun is shining it leaves a trace of charred paper. This figure was kindly lent by Messrs. Negretti and Zambra.

Later on it will be seen that glass absorbs much of the heat which falls on it, so that it is not a suitable material with which to experiment on refraction. Still these two examples suffice to show that radiant heat is refracted, and that in this respect also it behaves like light.

Diathermancy (διά, through; θερμαίνειν, to heat) is the capacity of a body for transmitting radiant heat.

Solids.—The double screen of Fig. 67 is fitted with a carrier like that for magic lantern slides, and stops between the plates, on which the carrier can rest. Slices of different substances can be placed in the carrier so that they come before the hole in the screen. Then all the radiation (whatever source of heat be employed — heated ball, flask of water or lamp) must pass through the substance before reaching the thermopile.

When the radiation from a heated ball is passing through the hole and falling on the thermopile, the spot of light has a wide deflection. A plate of clear glass ¼ inch thick is interposed; at once all the radiation is cut off and the spot of light comes to rest in the middle. A slice of rock-salt is then placed in a carrier and slid along so as to take the place of the glass, the spot of light instantly flies off to the side, showing that the radiant energy which was stopped by the glass passes easily through the rock-salt.

Melloni conducted experiments with a great number of substances and with different sources of radiant energy, estimating the relative degrees of diathermancy of different substances by the deviation of the galvanometer connected with a thermopile. A few of his results are tabulated.

Substance.	Percentage of Radiation Transmitted.		
	Oil Lamp.	Incandescent Platinum.	Copper at 100° C.
Rock-salt	92·3	92·3	92·3
Sulphur	74	77	54
Iceland spar	39	28	0
Glass	39	24	0
Gum	18	3	0
Alum	9	2	0
Sugar	8	1	0
Ice	6	0·5	0

This table shows that not only do different solid substances

transmit radiation in different percentages, but that this percentage differs with the nature of the source of radiant energy.

Rock-salt transmits equally the radiation from all the different sources of heat, but glass is impervious to the rays from the cooler source, while it transmits more than a third of that from the lamp.

Liquids. — To test the diathermancy of liquids a thin glass cell for holding liquids is fitted in a carrier. By using this it is seen that water intercepts the 'obscure' rays from the source of radiation, though, like glass, it is clear and transparent to light rays. On the other hand, carbon disulphide transmits the invisible heat rays freely.

Melloni's results for a few liquids are also given, the source of heat being an oil lamp. When an oil lamp is used the glass chimney absorbs some of the radiation, and the glass sides of the cell which contains the liquid also absorb some radiation, so that much radiation which glass will stop has already been removed from the beam.

Liquids.	Percentage transmitted.	Liquids.	Percentage transmitted.
Carbon disulphide . .	63	Absolute alcohol . .	15
Spirits of turpentine . .	31	Syrup or brine . . .	12
Olive oil	30	Distilled water . . .	11

Gases.—In all these experiments it has been taken for granted that the radiation passes without hindrance through the air. Dry air and the permanent gases transmit radiation, from whatever source of heat, without any hindrance, and behave as '*a practical vacuum as regards the rays of heat.*' It is different with vapours; they vary very much in their diathermancy among one another and with the nature of the source of radiation.

The experiments of Prof. Tyndall on their behaviour are described in his *Heat a Mode of Motion.* The simple experiment which he devised to illustrate the adiathermancy of water vapour will now be described.

Adiathermancy of Water Vapour.—A cube full of boiling

water is taken as the source of heat (Fig. 71), and as before a screen is interposed with a hole which allows the radiation to fall on the thermopile from a part only of the face of the cube. A cylindrical vessel about $3\frac{1}{2}$ ins. high and $7\frac{1}{2}$ in diameter, with a wire-gauze bottom, is placed between the cube and the thermopile, but not so as to intercept any radiation. A tube is led to a flat tin opening under the gauze with a fine rose.

The vessel is first filled with crystals of calcium chloride. When the air is gently forced through the tube it is dried by the calcium chloride and rises as a stream of dry air between the cube and the thermopile. The thermopile is 'corrected' by

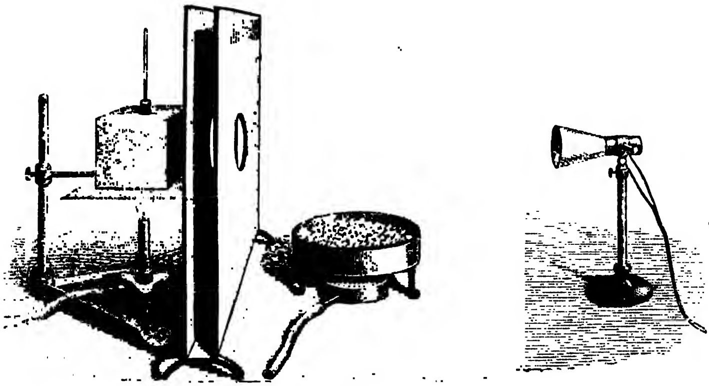


Fig. 71.—Adiathermancy of vapour.

placing another cube of hot water to warm its reverse side, and so bring the spot of light to the zero point.

The calcium chloride is now removed and the vessel is filled with fragments of stone moistened with water. When the air is forced through the tube it rises as a column of saturated air between the cube and the thermopile. The effect is immediate; a strong deflection of the spot of light shows that the saturated air intercepts the radiation to a great extent.

The water vapour surrounding the earth forms a screen, which tempers the rays of the sun and also prevents the heat of the earth from radiating into space. Regarding the earth as

a source of heat, at least 10 per cent of the radiation from it is intercepted by the vapour within 10 ft. of the ground.

The amount of vapour present in the air is continually varying, as has been observed above (p. 354), and even on a clear night the cooling of the earth's surface by radiation is checked by the vapour-screen which surrounds it.

In the same way the rays of the sun are tempered by our vapour-screen. Mountaineers suffer much from their heat. The quantity of vapour in the air diminishes gradually as we ascend (p. 355), and on a mountain side the pressure of water vapour may be very small. In such circumstances the sun's rays are almost intolerable. Tyndall says, "I never on any occasion suffered so much from the solar heat as in descending from the 'corridor' to the grand plateau of Mont Blanc, on 13th August 1857; though my companion and myself were at the time hip deep in snow the sun blazed against us with unendurable power. Immersion in the shadow of the Dôme du Goûté at once changed my feelings; for here the air was at a freezing temperature . . . we suffered not from the contact of hot air, but from radiant heat which had reached us through an icy cold medium."

Arctic explorers have commented on the great power of the sun in high latitudes owing to the dryness of the air. The pitch in the seams on a vessel's side has often been seen to boil while the air was below the freezing point.

The early morning in the summer is the time of least humidity, and the scorching heat of the sun is then very evident; the paint on doors which face eastward is often blistered by the untempered rays of the morning sun, though the temperature of the air may be moderate.

Obscure Rays.—If a prism or train of prisms of rock-salt be used to disperse the rays of light from a luminous source and form a spectrum, the radiation is not intercepted so much as when glass is used. Tyndall conducted many experiments in this manner with the object of finding out the heating power of the different parts of the solar spectrum (Fig. 72). The sun's rays before they reach the earth have to pass through our

vapour-laden atmosphere, and this cuts off a great deal of the obscure radiation. Still in the solar spectrum the heating effect of the obscure rays is twice that of the visible rays. The spectrum of the solar beam analysed at the high observatories, where the vapour layer is much thinner, shows a much greater proportion of obscure rays.

To test the presence of radiation of small intensity, Professor Langley invented the *Bolometer*, an instrument of great delicacy (see ELECTRICITY, p. 794). With its aid the obscure rays of the ultra-red spectrum have been mapped out and lines of no radiation detected in the solar beam there, similar to the Fraunhofer lines of the visible spectrum.

The obscure rays of a luminous beam may be isolated by

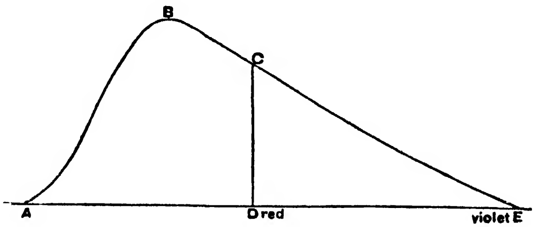


Fig. 72.—Heating power of solar spectrum.

using a filter, which allows them to pass but is opaque to light. Iodine, for example, is very opaque to light, but it is very diathermanous or transparent to the obscure rays; it may be dissolved in carbon disulphide or chloroform, either of which is very diathermanous.

By placing a filter of iodine before the opening of an electric lamp a beam of radiant energy, intensely powerful though quite invisible, may be projected and experimented on. These dark rays are of sufficient power to set paper alight and even to raise platinum to incandescence.

'Rays from an obscure source cannot,' Tyndall says, 'compete in point of intensity with the obscure rays of a luminous source.' One of his experiments will illustrate this.

A platinum wire spiral was arranged so that an electric current of gradually increasing intensity should pass through it. A beam of radiation from it was spread into a spectrum by means of lenses and prisms of rock-salt. In the part of the spectrum where there was a maximum heating effect a thermopile was placed. As the current was increased, the rise of intensity in the invisible rays was shown by the deflection of the spot of light.

In the following list the numbers give the intensity of the obscure rays proceeding from the spiral as it showed different colours whilst being heated to incandesence.

Dark	1	Orange	60
Dull red	13	Yellow	93
Full red	27	White	122

This shows how the obscure rays are immensely increased as the source of heat becomes luminous.

The proportion of the heating effect of the luminous rays to that of the obscure rays varies very much in beams from different sources of heat.

The radiation from an incandescent platinum wire consists of 1 part luminous to 23 parts obscure, and from the brilliant part of a gas flame 1 part luminous to 24 parts obscure. From an arc light the proportion is 1 part luminous and 9 parts obscure.

This enables us to understand why it is that various substances are diathermanous in such different degrees to radiation from different sources.

Radiant heat is identical with radiant light; it differs from red light as red differs from blue. Just as different substances absorb rays of light from different parts of the spectrum and so have different colours, so different substances absorb some of the rays of heat, which sources of heat are radiating, in different proportions; for example, glass transmits heat rays from a lamp to a considerable extent, but none from a copper ball at the temperature of boiling water, because it is opaque to rays from the invisible part of the spectrum.

Greenhouses.—The rays of the sun traverse the glass of a greenhouse because they are from the luminous part of the spectrum, and they heat the solid objects in the house, the walls, floor, etc.

The obscure rays which these heated objects give out cannot penetrate the glass, which is thus 'a trap to catch a sunbeam.'

Absorption.—Whilst the air and the permanent gases offer little or no obstruction to the passage of the heat rays, vapours as well as liquid and solid substances vary in their diathermancy. The question naturally arises, What happens to the heat rays which they stop? and there is not much difficulty in suggesting an answer—the heat rays must heat the substances which stop them. For example, the glass of a greenhouse, though it allows the luminous portion of the sun's rays to pass through, stops obscure rays and becomes very hot.

If a plate of rock-salt and a plate of glass be placed alongside one another in the hole of a screen through which is passing a beam from an electric arc, the glass becomes hot while the rock-salt remains cool. It is the same with cells of water and of carbon disulphide, the water absorbs the radiant energy from the lamp and is heated, the disulphide allows the rays to traverse it and remains cool.

Radiation and Absorption.—The transformation of the heat energy into energy of vibration of the light-ether takes place at the surface of the hot body. As might be supposed, the character, nature, texture, or one might say 'grain' of the surface affects the amount of energy which is transformed into vibration.

For example, it is a well-known fact that radiation takes place slowly from bright surfaces: steam-pipes, teapots and hot-water jugs, if kept bright, do not lose heat so quickly as dull surfaces.

In common parlance the word '*Radiation*' is used for this loss of heat from the surface of bodies, while in more scientific language it is used for the ether vibrations themselves. Similarly, with the term '*Absorption*,'—the reverse process, transformation of energy of ether vibration into heat energy. This takes place at

the surface of the body, which is being heated by radiation, and the 'grain' or texture of the surface affects its power of absorbing vibrations in the form of heat. A bright body takes up less heat from radiation which falls on it than a dull body does. The bright fire-irons remain cool for some time after a fire has been lighted, while a dull black fender becomes intensely hot. And this process is called *Absorption*, so that we have such a rule as this—The absorption and radiation of dull bodies is greater than that of bright bodies.

The reader cannot fail to observe that the words 'radiation' and 'absorption' are not used in the same sense as they were used at the beginning of the chapter. They refer to a loss or gain of heat at the surface of the body, while absorption was applied above to the heat which is received by a substance through which radiant energy is passing with more or less loss on the way.

Experiments on the radiation and absorption at different surfaces were made by Melloni and by Sir John Leslie. Since they both used hollow metal cubes filled with hot water as the source of heat, such cubes are called 'Leslie's cubes' or 'Melloni's cubes' by English or French writers, as the spirit of patriotism dictates. Leslie's cube is shown in Fig. 73.

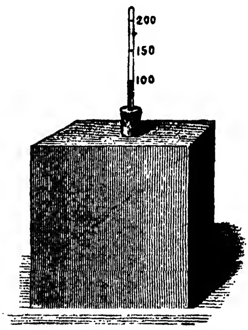


Fig. 73.—Leslie's cube.

They are usually made with an edge of about 6 in. (15 cm.), and a thermometer graduated on the stem passes through a cork which stops the hole through which the cube is filled and emptied.

Radiation from Surfaces—*Radiation from a bright surface is less than from a dull one.*—A Leslie's cube of pewter or tin has one of its faces bright; on one face the metal is smeared with grease; one face is painted and one covered with lamp-black. The cube is placed on a stand, the top of which can be turned round (Fig. 74) so as to present each face in turn to a thermo-

pile. The cube is filled with boiling water, and when the bright face is turned to the thermopile the spot of light is deflected but little. If a greasy cloth be rubbed over the bright tin, or if the greased face be turned to the pile, a smart deflection takes place, showing a great increase of radiation from the cube. The painted surface causes a strong deflection, but the greatest movement occurs when the lamp-blacked surface is turned to the thermopile.

By covering the faces of the cube with different substances —cloth, glass, dull sheet-iron, velvet, etc.—and noticing the

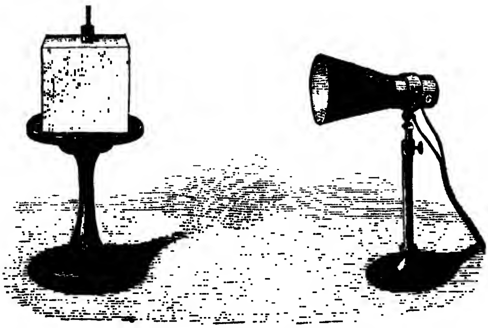


Fig. 74.—Radiation from different surfaces.

deflection of the spot of light in each case, substances may be arranged in the order of their powers of emitting radiation. Lamp-blacked surfaces are the best radiators and bright metallic surfaces are the worst. In such experiments the cube may be kept at the boiling point by a steam-pipe led into it.

The experiment is also conducted with several cubes, with their whole surfaces covered with different materials. They are all filled with boiling water, and being placed on flannel or cork so as to lose no heat by conduction, their rate of cooling is observed by reading the thermometers placed in them. Here it is assumed that the cooling is wholly due to the radiation from their surfaces.

The bright metal cubes cool very slowly, while a cube which has been coated with lamp-black cools rapidly.

Radiation is independent of colour.—So long as the texture of the surface is the same, a difference of colour does not alter the amount of radiation. A Leslie's cube is painted on its four faces with paints of the same 'surface' but of different colours; it is filled with boiling water and placed on the revolving stand. No perceptible change is seen in the position of the spot of light as the different coloured faces are turned to the thermopile.

The same may be shown by comparing the rate of cooling of different coloured cubes as before. So long as the paint on each is of the same 'surface,' the thermometers in the cubes all continue to show the same reading as the water cools; the colour of the paint does not affect the rate of cooling.

If a silver and an earthenware teapot be placed on a support, at equal distances, and the collector of the thermopile be turned to each; the silver pot hardly gives out any radiation, while the spot of light flies away to the side directly the collector is turned to the earthenware pot; a glass bottle full of boiling water radiates much more freely than a tin or metallic vessel, and in all cases it is the material and surface of the vessel which affects the radiation from it.

Absorption at Surfaces.—Just as the texture or grain of the surface influences the intensity of radiation from it, so what is now to be styled 'Absorption'—the effect of the vibrations of the light-ether in imparting heat to a body—varies with the character or texture of the surface.

Absorption is less at a bright surface than at a dull one.—Leslie's cubes, with different surfaces—bright, greased, painted, lamp-blacked, etc.—and all containing water at the same temperature, are placed round a source of heat, such as a heated ball or before a fire. In the latter case the cubes should be placed in a row on flannel or cork, and be surrounded by a meat screen, so that a great deal of heat may be radiated on to them. Then if the thermometers in the cubes be read continuously, a great difference will be observed in the rate at

which the water in the cubes is heated. The temperature of the water in the bright cube rises slowly, and that in the lamp-blacked cube faster than in any of the others. From a series of such experiments a table may be made, showing the comparative powers of Absorption and Radiation of different substances, and these two tables will be found to be identical. This shows that—

Good radiators are good absorbers.

Bad radiators are bad absorbers.

Influence of colour on absorption.—Leslie's cubes painted with different colours, but with the same class of surface, are placed as before round a source of heat — a heated ball or hot fire — all resting on flannel or cork, so that all the heat they receive is by radiation. In each is placed a thermometer engraved on the stem, with which the temperature of the water can be read without moving the cube.

Then in this case there is no practical difference in the readings of the thermometers as they rise—the water in each cube is heated at the same rate.

An experiment which is due to Franklin has led many people erroneously to conclude that the colour of substances alone influences absorption. Several cloths of different colours were laid out on the snow in sunshine, and as they did not all sink at the same rate in the snow Franklin concluded that they absorbed heat differently because of their difference of colour.

Tyndall devised an experiment to confute this idea. Two equal cards are sprinkled, the one with powdered alum and the other with powdered iodine, and they are placed before a hot fire. In a little while, if they are taken up, the one which is white with alum is very hot, while that which is nearly black with the iodine is comparatively cool. Here a white object is heated by radiation which does not heat a dark one.

The alum is opaque to the 'obscure' rays, while iodine is diathermanous. The heat-rays traverse the iodine, and are reflected at the further surfaces of the little crystals without any

perceptible heat being absorbed. The alum absorbs the heat rays, which cannot penetrate it, and becomes very hot.

A red cloth is red because it absorbs the green rays; and a violet cloth in a similar way absorbs the radiation of the heating portion of the spectrum.

In this way dark clothing becomes hot, while light clothing reflects much of the sun's rays and remains cool. So long as radiation consists wholly or chiefly of obscure rays, absorption is independent of colour, but the sun's rays, so far as they come from the luminous part of the spectrum, are more absorbed by dark bodies than by light.

Radiation and Absorption Compared.—The following experiment was devised by Ritchie to show the connection between Radiation and Absorption. A Leslie's cube is placed on a rest, and at the same height, and with faces equal and parallel to those of the cube, are two square boxes connected with one another by a glass tube. Some coloured liquid occupies the lower part of the tube, so that with the boxes it forms a differential air-thermometer (Fig. 6, p. 271). With this apparatus all the different comparisons described above may be directly made. But the apparatus is specially suited to show the equality between the powers of Absorption and Radiation of different surfaces.

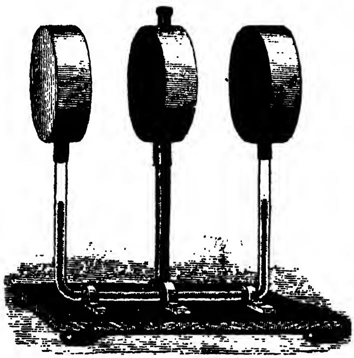


Fig. 75.—Ritchie's boxes.

The middle box in Fig. 75 is called a 'Leslie's cube,' as that is the form usually adopted for the source of heat. In Lecture-Room apparatus such as that shown in the figure it is frequently not made cubical.

The boxes have their inside faces, the one polished and the other blackened. The cube has its opposite faces, the one polished and the other blackened. If it be filled with boiling

water, and its polished face be turned to the box with blackened face and its blackened face towards the polished box, no movement is seen in the column of liquid. The blackened face of the Leslie's cube gives out radiation more freely than the polished face, but the blackened box absorbs radiant heat more freely than the bright box. Thus the effects are balanced and the two boxes are equally heated by the Leslie's cube. This experiment was devised to make it apparent to an audience that the powers of Absorption and Radiation of different substances or rather surfaces are practically identical, that is—Good radiators are good absorbers.—Bad radiators are bad absorbers.

If the other two faces of the cube be similar, whether bright or painted, and these two faces be turned to the blackened and polished boxes, the blackened box is heated much more than the bright box owing to its greater power of absorption. The column of coloured liquid in the arm of the thermoscope below the blackened box is depressed below the other column.

The difference between the absorption of radiant heat by bright metal and by other substances is very often noticeable in ordinary affairs. A new kettle boils slowly, and is much improved when its bottom gets black.

The thinnest conceivable coating of metal, gold-leaf for instance, protects the wood underneath it from radiation. If a board lettered in gold be exposed to radiation from a strongly heated source, the part underneath the gold is found quite protected when the wood all round is charred and blackened.

If two thermometers be placed in the sunshine, one of which has its bulb clean, the other, if its bulb is blackened, will be found to give a much higher reading. Glass, however, is a good radiator and a good absorber compared with metal.

Reflecting Power—*Comparison of reflecting powers of different substances.*—A Bunsen flame or a heated ball is used as a source of radiant energy. Different substances are used as reflectors at A (Fig. 76), and a thermopile is so placed that its axis makes an angle with the reflector equal to that made by the incident rays. A double screen is interposed between the source of heat and

the thermopile, so that the only rays which reach the face must be those reflected by the substance to be examined.

By comparing the deflection caused by the rays from different substances, these can be arranged in the order of their relative powers of reflection.

It is then seen that those substances which absorb most reflect least radiation. A lamp-blacked surface absorbs a great deal of heat, and reflects but little. It must, however, be remembered that the substance which absorbs well soon becomes heated, and then emits radiation freely. The experiment described above

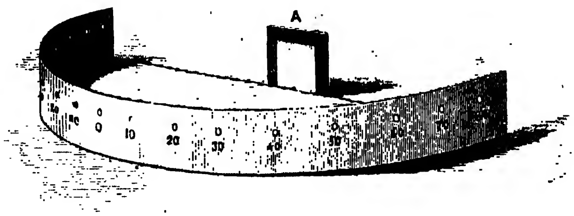


Fig. 76.—Reflection instrument.

must be done quickly, so that the reflecting substance has no time to become heated.

Distribution of Radiant Energy.—When the vibrations of the light-ether reach the surface of any body they are partly reflected and partly enter the body. Those which enter the body are partly absorbed, that is, transformed into heat-energy. If the substance be diathermanous most of them pass on and are reflected back from the inner surface. The part of them which is absorbed raises the temperature of the body, which then emits radiation in turn. So then, there are in all four ways in which radiation falling on a body is disposed of, and we see that—

Good absorbers are good radiators and bad reflectors.

Good reflectors are bad absorbers and bad radiators.

In adiathermanous substances more radiant energy is reflected and absorbed, and little or none is refracted.

In diathermanous substances more is refracted and less is absorbed and reflected.

The sum of the radiation which enters the substance, whether absorbed or refracted, together with that which is reflected, must be equal to the total radiation falling on the surface.

Radiation Pyrometer.—A useful application of the laws of radiation is due to Professor Féry of Paris. The radiation which emanates from a hot body, or which passes out through an observation hole in the wall of a furnace, is brought to a focus by a concave mirror. In this focus is a thermopile, whose temperature is raised by the radiation falling upon it, and the rise of temperature is read or recorded by a galvanometer.

The Stephan-Boltzmann radiation law—*The radiant energy emitted by a black body is proportional to the fourth power of the absolute temperature of the body*—has received abundant experimental support through the widest range within which temperature measurements can be made. The graduation of the galvanometer scales is based upon this law. It is strictly true only of perfectly black bodies, but when the interior of a furnace or combustion chamber is nearly at the same temperature throughout, the wall, seen through a small hole, is *effectively black.* The temperature reading is independent of the distance (see p. 388); for example, the reading obtained for the temperature of a stream of molten steel was precisely the same—1200° C. —whether the instrument was set up 3 feet or 60 feet away. It is an advantage to be some way off; also the sensitive part of the thermometer is not raised to destructive temperatures.

These most interesting instruments are introduced by the Cambridge Scientific Instrument Co., to whom this description is due.

Cooling.—It has been assumed, in speaking of experiments with Leslie's cubes, that cooling is due to radiation, and that the rate at which the temperature of the water in the cube falls is a measure of the radiation from its surface.

Convection currents in the air also carry off heat, and are the greatest cause of cooling.

In his public experiments with liquid air (19th January 1894)

Professor Dewar placed the liquid air in a vessel surrounded by a vacuum jacket immersed in liquid oxygen and surrounded by a second vacuum jacket. In the vacuum there could be no convection currents, and conduction of heat was minimised by the liquid oxygen. No access of heat was possible except by radiation, and this was shown to be very small indeed.

Rate of Cooling.—It is a matter of common observation that bodies at a high temperature lose heat more rapidly than bodies that are cooler. Newton's Law of cooling is that *The rate of cooling is proportional to the difference between the temperature of the body and its surroundings*, *i.e.* a body at a temperature of 80° C. cools twice as fast as one at 65° C. in air at 50° C.

The rate of cooling depends also on the nature of the surface of a body; the intensity of heat-energy emitted from a body has been shown to depend on the nature of its surface. It also depends on the substance by which the body is surrounded. Adiathermancy in the surroundings would stop radiation altogether, and more or less diathermancy assists or prevents it.

The earth is always being cooled by radiation from its surface into space. This would take place without hindrance if the earth were surrounded only by air, which is diathermanous to the obscure rays from the earth's crust. But the water vapour in the air stops a large proportion of the radiation, according to its degree of saturation.

Cooling by radiation is made use of in India; for in the evening pans of water, exposed to the open sky, cool until they freeze. They are placed on deep beds of dry straw, which cut off the conduction and radiation from the earth. The temperature of the air falls, though it is always above the freezing point. Still it is dry, and evaporation proceeds rapidly from the surface of the pans, thus lowering the temperature. Radiation from the water into space also proceeds rapidly, and the temperature of the water falls so low that the whole of it is turned into ice. A high wind would ruffle the water and stop cooling, but a slight breeze is favourable to the formation of ice. It will be observed that the evaporation and the radiation are both rapid because of

the dryness of the atmosphere. Water vapour acts as a cloak to the earth, and keeps in its heat. Gardeners can tell from the temperature and hygrometric condition of the air whether it will freeze at night, and on a clear dry night are prepared with coverings, often very slight, still sufficient to check the radiation, and so protect their tender plants.

Prevost's Law of Exchanges.—Cooling also depends on the neighbourhood of cool bodies. This is not quite the same as cooling due to a surrounding substance of a different temperature. If in the experiment described on p. 389 a piece of ice be substituted for the heated ball in the focus of the mirror, the spot of light immediately flies off in the opposite direction, showing that the thermopile is cooled by the ice just as it was heated by the ball. *Prevost's Law of Exchanges* is that a body is continually radiating energy in every direction, and absorbing that which falls on it. Bodies are thus not only giving out but receiving radiation from neighbouring bodies. If a body and its surroundings are at the same temperature, the radiation received balances that given out, and the temperature of the body does not fall. If, on the other hand, two bodies near one another are at different temperatures, there will always be a tendency to equality of temperature. This is what is proceeding in the case of the ice and the thermopile; the blackened face is radiating more heat than it receives, and the spot of light shows a fall of temperature at the junctions of the thermopile.

Mobile Equilibrium of Temperature.—Hence, both radiation and absorption are always going on at the surface of a body. When cooling, it is radiating more energy than it absorbs, and the converse when it is being warmed. When neither is the case, but the body and its surroundings are at the same temperature, there is equilibrium between the absorption and radiation. But to avoid, in speaking of this continuous flux, the idea of rest which attaches to the word equilibrium, the expression *Mobile Equilibrium of Temperature* is applied to a condition of equally balanced gain and loss of heat-energy.

CHAPTER XII

Transmission of Heat—Conduction and Convection

Conduction—Conductivity—Conduction in Fluids—Conduction in Solids—Values of Thermal Conductivity—Method of Fourier and Depretz—Consequences of Conduction—Convection.

Conduction.—In the definition of temperature given at the beginning of the subject of Heat, the flow of heat from point to point is referred to as a matter of common knowledge. It is in fact the test of temperature; heat flows from a point at a higher temperature to one at a lower. Now heat flows in various ways, of which one, Radiation, was the subject of the last chapter; we can stand before a fire and warm our hands by radiation.

But we can also warm our hands by putting them in warm water; in this case, heat is communicated by contact, heat flows from the water to the hand in contact with it; such flow of heat is called *Conduction*. Suppose the water were cooler than the hand, the reverse would take place, heat would flow from the hand to the water in contact with it. *Heat is transmitted by Conduction when any particle of a body is raised to a higher temperature owing to its contact with a particle hotter than itself.*

Conductivity.—All substances do not conduct heat equally well. If a silver spoon be left in a cup of hot tea the handle soon becomes very hot, while if a bone spoon be left in the tea its handle is not perceptibly warmed. Metals are very good conductors of heat, and when turning a hot tap or removing a

kettle from the fire, a piece of woollen, cotton or other substance which conducts heat badly is used, to avoid burning the hand by contact with the metal.

Conduction in Fluids.—If a piece of ice be weighted and so kept at the bottom of a long narrow test tube filled with water,

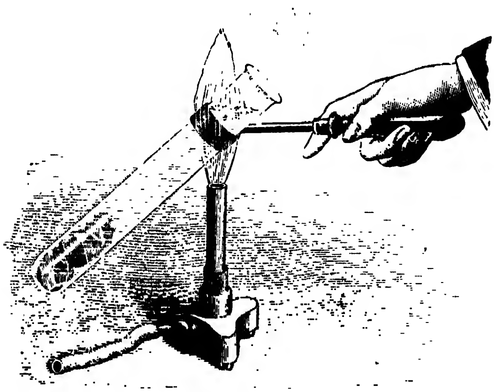


Fig. 77.—Conduction of water.

the water at the upper part of the tube may be boiled over a spirit lamp or gas flame without the ice being melted (Fig. 77). The experiment shows that water conducts heat badly. It is very difficult to estimate the conductivity of liquids or gases because their particles are free to move; convection currents may be avoided to a certain extent by heating a liquid from the top as above.

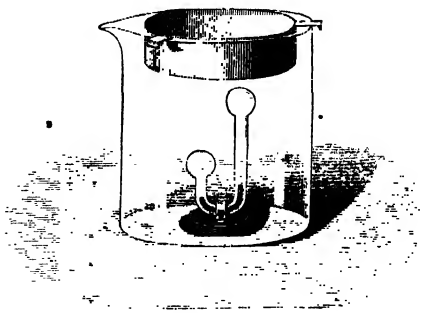


Fig. 78.—Conduction of water.

Again, a thin copper vessel is provided with ears which rest on the sides of a beaker of water (Fig. 78). In the beaker

is a thermoscope with one bulb higher than the other, and when all is at the same temperature the position of the liquid column is noted. The copper vessel is then filled with boiling oil or water and the water underneath is heated by conduction only. The thermoscope shows no movement for a long while, showing that water is a very bad conductor of heat.

A similar experiment may be made with other liquids, or with gases, but in gases it seems impossible to avoid convection currents. Besides this, liquids and gases spread against gravity by diffusion (see PROPERTIES OF MATTER, p. 144), and this must be allowed for in observations of conductivity of fluids.

Conduction in Solids—INGENHOUSZ TROUGH.—A long copper trough has several short tubes projecting from it near the bottom, into which corks are inserted. Through the middle of each cork passes a rod of metal, slate, glass, or other substance, one end of which projects into the interior of the trough (Fig. 79), and the other end extends about 8 or 10 inches outside.

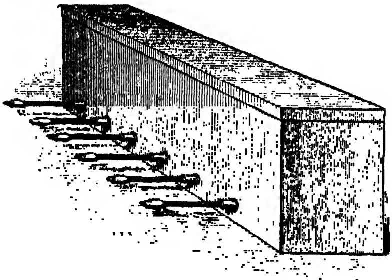


Fig. 79.—Ingenhousz trough.

The outer part of these rods is dipped in paraffin wax, which melts at 140° F. (60° C.) and cooling on them forms a solid wax coating. When the trough is filled with boiling oil the heat flows along the bars by conduction and melts the wax. The experiment is meant to show the relative conductivity of different solids. The wax melts probably to the end of the copper bar, which shows that copper is an excellent conductor of heat, and the same would be the case with silver if the laboratory were extravagant enough to provide a silver rod. The wax on the brass and iron melts for some distance; on glass and slate for a very short distance, and on wood only so much as is melted by the radiation from the trough. Except in the case of the best

conductors, the heat is radiated or carried off by the air more easily than conducted along the rod, and so the end does not reach the melting temperature. The ends of the rods in Fig. 79 are fashioned into cups, a familiar adaptation to Lecture-Room needs. A small piece of phosphorus is placed in the cup, which ignites when the temperature of the rod rises sufficiently, as in the following experiment.

RING OF METALS.—Four flat bars of different substances, *e.g.* copper, iron, zinc and slate, are fastened as radii to a wooden ring, so as not to touch one another at the centre (Fig. 80). They can then all be heated by a gas burner at the centre and the heat will flow along the bars. In a cup at the outer end of the bars is a small piece of phosphorus which ignites on the bar reaching a temperature of about 111° F. (44° C.). The phosphorus at the end of the copper bar soon ignites, followed by that on the brass; later that at the end of the iron bar lights, but that on the slate never reaches the temperature of ignition. This experiment, like that with the Ingenhousz trough, is meant to show relative conductivity plainly and roughly to a class. Before describing any more exact determinations of the power of substances to conduct heat a definition of thermal conductivity is required.

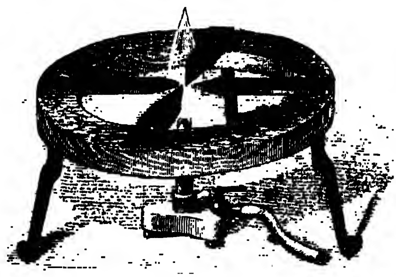


Fig. 80. Ring of metals.

Values of Thermal Conductivity.—THE THERMAL CONDUCTIVITY OF A SUBSTANCE *is the number of thermal units which pass per unit of surface per unit of time through a slab of unit thickness, whose sides are kept at a temperature differing by one degree.*

In the rough experiments given above the apparent value of the conductivity is influenced by the specific heat of the

substances. If the specific heat of a substance is comparatively large it takes some time for the heat to flow along it, because a greater quantity of heat is required to raise a certain portion though one degree of temperature. An experiment of Tyndall's illustrates this.

The thermopile is laid on its face and small cylinders of various substances, say 2 inches high, and of the same diameter as the face of the thermopile, are provided for the experiment (Fig. 81).

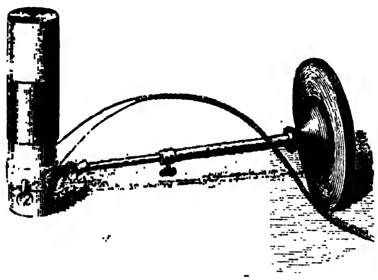


Fig. 81.—Conduction and specific heat—Tyndall's experiment.

A cylinder of iron of the same diameter is used for the source of heat after being immersed in boiling oil.

Each substance is laid on the thermopile in turn, and the hot iron placed on it. Then the time which elapses before the spot of light moves shows how long it takes for the heat to traverse the substance. This is a very short time in the case of copper, brass, iron, etc.; but with wood, stone, glass, etc. no heat sufficient to cause a motion of the spot of light is able to flow through them to the face of the thermopile.

But the experiment does not really decide the value of the thermal conductivity of substances. Take a cylinder of bismuth and place it on the thermopile; place the hot iron on it and note the time taken by the heat to reach the face of the thermopile, then take a similar iron cylinder, the time is greater. From this an erroneous conclusion would be drawn that bismuth is a better conductor than iron. The iron is in fact a much better conductor than bismuth, but the specific heat of iron is more than three times that of bismuth, so that it requires more than three times the quantity of heat to raise the iron than it does to raise the bismuth through one degree of temperature.

Consequently, in the Ingenhousz trough, more rapid melting

of wax on a rod does not show it to be the better conductor, but what does show it is the greater length to which the wax is melted when the flow of heat and its dispersion is steady.

Method of Fourier and Depretz.—This mode of determining the value of thermal conductivity depends on the measurement of the steady flow of heat along a bar, which is what the definition contemplates.

Equal bars of various substances are provided with small cavities at equal intervals, which may form mercury cups. These

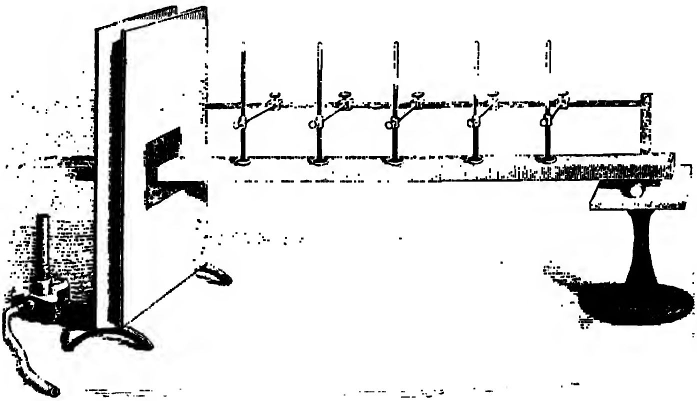


Fig. 82.—Conductivity of metals.

bars are heated at the extremity by a spirit lamp and thermometers dip into the mercury.

The experimental rod and a standard rod of pure copper both butt into an iron junction-piece filled with solder, which is kept melted by a Bunsen burner and serves as a source of heat. When the burner has been lighted some time the whole is in a steady condition, and readings of all the thermometers show the flow of heat or the rate at which the temperature decreases along the rods.

Fig. 82 shows a Lecture-Room arrangement of half the experiment. The junction piece and the standard rod do not appear, but the figure may illustrate the experiment.

Independent experiments must be made with the rods to determine the quantity of heat which they lose per second from each unit of surface at each temperature. This is done by heating the whole of each bar to the temperature of the melted solder, and then noting the time which it takes to cool at each temperature. It will be seen that calculation from these data will give the quantity of heat which is flowing along the bar and crossing a given section of the bar in each second. The standard bar serves to regulate the conditions of the experiment so that they may be the same when each of the rods is experimented on.

Consequences of Differences in Thermal Conductivity.—The story runs that a young bride, among whose wedding presents was a silver teapot, was anxious that her friends should realise, in these days of electro-plate, that it was the genuine article, and so she occasionally let her fingers touch it absently, hastily exclaiming 'Oh dear! how hot real silver is!' And so it is, if its conductivity be compared with its rival, German silver. Hence whilst a silver teapot loses less heat by radiation than an earthenware pot, still it loses heat by convection, and more than a cooler pot would. Also, according to Newton's Law of cooling, it loses more heat than a cooler pot, so perhaps the ladies are not wrong after all in putting a non-conducting woollen 'cosy' over their teapots.

The non-conducting properties of animal and vegetable substances are made use of in handles for hot vessels, and in clothing the body with flannel or Jáeger clothing. Clothing maintains next to the body a coating of air which is at the temperature of the body, and so avoids its cooling by radiation, evaporation, or convection. Again, wisps of straw are wound round trees and pipes to keep them from losing heat in a frost; ice is packed in flannel or sawdust to prevent heat from reaching it. Steam-pipes and boilers are coated with hair-felt and bone-meal or asbestos packing to keep them from losing heat. Asbestos is a fibrous silicate and is a bad conductor, for the same reason as fur or feathers. The fibres are bad conductors, and

there are interstices between the fibres over which the heat does not pass by conduction. Fur or down keep the heat of the body from escaping. A swan or duck will float for hours on water little above the freezing point, its feathers and down prevent its heat from escaping to the water.

Water may be boiled in a paper bag; the heat is conducted through the paper so that the temperature of the paper is never much above the boiling point. A cylinder is built up, half of wood and half of copper; now if this be wrapped round with paper and held over a lamp the paper next the copper remains whilst that touching the wood is burned. The copper, being a

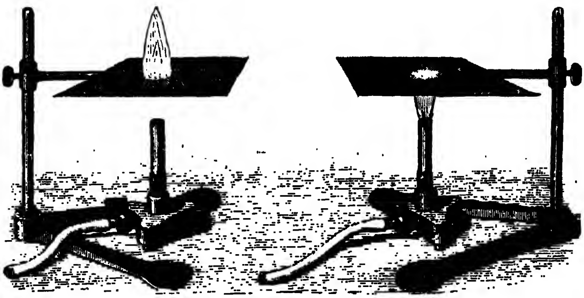


Fig. 83.—Flame and gauze.

good conductor, carries off the heat of the flame, and the paper remains cool, while the wood leaves the paper to its fate.

Davy Lamp.—If a sheet of wire-gauze be held over a gas flame, the flame does not pass through it; again, if the flame be extinguished the gas comes up through the gauze and may be ignited at the top; the flame will not go down to the burner (Fig. 83). Both of these experiments illustrate conduction, for the heat of the flame near the gauze is distributed by the wires, and the temperature of the gauze on the side away from the flame is not high enough to cause combustion.

This is used in the Davy lamp, an invention which affords some security to miners. They are in danger of explosion and fire from ignition of the dust of the mine or from the sudden

appearance in the workings of coal-gas, liberated by the pick from some cavity in the coal. The gas is poisonous, but it is also explosive when mixed with air. In the Davy lamp the flame of an oil lamp is shrouded in wire-gauze (Fig. 84); and if gas be present it burns inside the lamp with a dull blue flame. This is a warning to the miner to leave the workings till ventilation has restored the atmosphere to a safe condition. For the reason illustrated in the experiments above, the flame will not pass through the gauze unless there is some fracture, or unless the flame is forced through by some shock, such as blasting, or from the lamp being swung or carried rapidly. Modern lamps have glass opposite the flame, with wire-gauze above and below the glass. Such a lamp gives better light, but it is owing to the invention of Sir Humphrey Davy that it is used with safety in places where a naked light could not be safely employed.

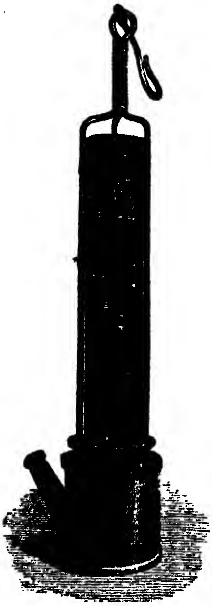


Fig. 84.—Davy lamp.

Convection.—Heat may also be transmitted from place to place in a fluid by the actual motion of heated particles, and this is called *Convection.* The fluid is heated by conduction and becomes lighter, so that it rises as a result of its expansion, and carries off the heat with it. This subject is discussed in connection with expansion in Chaps. II. and III.

As there described, the great ocean currents, as well as the steady and variable winds, which are so important to the sailor, are all of them convection currents on a large scale.

It is of the very essential character of heat that it should spread in all directions, until an equilibrium of temperature is attained, and this is always going on.

WAVE MOTION, SOUND, AND LIGHT

BY

W. D. EGGAR, M.A.
ASSISTANT MASTER, ETON COLLEGE

PREFATORY NOTE

THE chapters on Sound have had the great advantage of Lord Rayleigh's criticism. The author is also very grateful to Dr. C. H. Lloyd and Mr. A. M. Goodhart, who have read through the proof-sheets and made some valuable suggestions and corrections from a musical point of view. He is indebted to Sir Walter Parratt for some valuable information on the subject of Resonance. The chapters on Light owe much to Mr. R. T. Glazebrook's lectures; and in this subject the author's special thanks are due to the Rev. R. H. Whitcombe for his careful reading of the proof-sheets and for his suggestive comments on them.

WAVE MOTION

CHAPTER I

Harmonic Motion

Wave Motion on Water—Motion of a Disturbance—Medium necessary—Periodic Motion—Simple Harmonic Motion—Composition of S.H.M. with Rectilinear Motion—Vibrations of a Rod—Composition of two or more S.H.M.'s—Wave Forms resulting therefrom—Vibrations of a System of Particles—Waves in Water—Fourier's Theorem—Resolution of Complex Periodic Motions.

Wave Motion.—We are all familiar with the effect produced by dropping a stone into a still pond. The surface of the pond is covered with circular wavelets widening out from the central point where the stone fell. Does the water really move outwards from this centre? We can decide this for ourselves by noticing the motion of some leaf or piece of stick on the pond. As a circle reaches it, it rises and again falls. But it does not move outwards with the wavelet; it keeps its old place in the pond. This tells us that the water itself is not moving outwards from the point where the stone fell; for if it were, the leaf would move with it. The motion consists in each portion of the pond's surface in turn rising and falling with a slight motion from side to side.

Watch a river when the wind is blowing up stream. The motion of the wavelets will give the impression that the stream is flowing backwards; but observe a bubble on the surface, and it will be found to be moving steadily down stream, rising and

falling as it meets each wave. A person in a small boat, or swimming in the sea, will notice the motion imparted to the boat or to himself, by each successive wave. Let the reader imagine himself in the trough between two wave-crests facing the advancing wave. As it comes, he is carried forwards and upwards until half-way up its face. Then the forward motion ceases, and a backward and upward motion follows until he is on the crest of the wave. The backward motion continues till he is half-way down the slope of the retreating wave, and he is then carried forwards again, but still downwards, till he is once more in a trough. He has in fact described something like a circle, and his movements have been copied from every portion of the surface of the sea in front of him, and will be copied by every portion of the surface of the sea behind him. The steady onward movement of the waves is not an onward movement of the water. What we see moving onwards is a state of things, a shape, a wave form.

Lay a rope out straight on the ground. Give a sudden jerk to one end of the rope, and a wave will travel along it, caused by each portion of the rope communicating the jerk to the next portion. Another familiar instance of wave-motion is given by a barley field in the wind; but here it must be noted that the effect is produced by the air acting on each barley ear in turn, not by each ear forcing its neighbour down.

Motion of a Disturbance.—We have in the preceding article spoken of the motion of a state of things as distinct from the motion of a material body. To make this distinction clear, let us imagine a royal procession passing along a crowded street. With the moving carriages we may notice the movement of a disturbance among the crowd, first one man cheering and waving his hat, then the man next him, and this state of things travelling along the crowd parallel with the moving procession. We describe it by saying that a wave of excitement travels along the crowd at the same pace as the carriages. It should be noted also that the presence of the crowd is necessary for the passage of the wave of excitement, in the same way that a wire is

necessary for the transmission of a telegraphic message. In the absence of a crowd no excitement could travel. The crowd is the **medium** which transmits the excitement.

In previous instances we have had water, a rope, a barley field acting as *media* for the transmission of a disturbance. We may mention here that sound is an example of a disturbance of this kind, and that sound cannot travel without some medium, some material substance, such as air, or wood, to transmit it. In the case of light we have, in the universal opinion of men of science, another example of wave motion; and as light can travel from the sun and stars to us, it follows that inter-stellar space must be filled with some *medium* capable of transmitting the disturbance which, when it affects our eyes, we call *Light.*

Periodic Motion.—*Swings, Oscillations, Vibrations.*—We notice the leaf on the pond bob up and down with each wavelet in turn. It is necessary therefore to consider the nature of this movement before proceeding to consider the wave as a whole. The motion of the leaf, if we neglect the slight sideways movement, is an oscillation up and down, above and below the position it occupies when the surface of the pond is still. Or taking the sideways motion into account, we may say that the whole motion of the leaf is a *periodic motion.* By periodic motion is meant a motion which continually returns to the same condition after equal intervals of time. The length of these intervals of time is called the *period* of the motion. Oscillations, vibrations, swings, are other names for instances of periodic motion. The simplest and most familiar instance we can take is a pendulum.

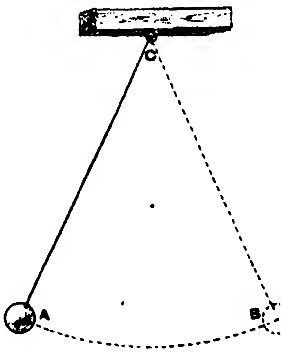


Fig. 1.—Simple pendulum.

A heavy ball A hanging by a string from a fixed support C represents a Simple Pendulum (Fig. 1). When at rest it hangs vertically under the force which gravity exerts on it—its weight.

Now, if it be pulled to one side and let go, its weight pulls it back to its first position, but in doing so, communicates enough speed to carry the ball past its lowest position, and to a distance on the other side which, but for the resistance of the air, would be equal to the first displacement. Then the ball swings back again, each swing or oscillation being 'damped' by the air. If the times of the swings be noted, it will be found that they are equal. This is approximately true even when the arc of the swing AB is large.

Simple Harmonic Motion.—Uniform motion in a circle may be obtained by making the ball of the pendulum swing in a

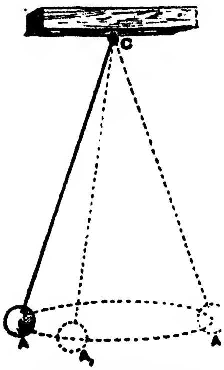


Fig. 2.—Conical pendulum.

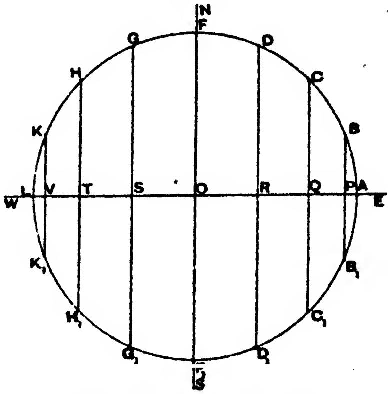


Fig. 3.—Simple harmonic motion.

circular path. We have then what is known as the *conical pendulum*, because the string describes a right circular cone. If we view the motion of the ball from a point vertically above or below the point of support C, we shall see it move in a circle; but if our point of view is from the side, the ball will appear to describe an ellipse (Fig. 2); and if we lower our eye into the plane AA_1A_2, it will seem to move backwards and forwards in a straight line. The apparent motion of the ball will then be nearly a Simple Harmonic Motion, approaching it more closely as the observer's eye is withdrawn farther. This can be better explained by the accompanying figure (Fig. 3).

Divide the circular path into sixteen equal parts. As the ball moves from A to B it will appear, to an eye far enough off in the direction S, to move from A to P. As it moves from B to C, the apparent path will be from P to Q, and so on. It can easily be seen that the distances AP, PQ, QR, etc. (which correspond to equal arcs on the circle, and therefore to equal periods of time), are larger as we approach O. The ball will appear to stop at the points A and L, and to be moving most quickly as it passes through F and F_1. The apparent motion in the path APQROSTVL, and back again, forms what is known as a *Simple Harmonic Motion*.

The length OA or OL of the apparent half-swing is called the *amplitude* of the motion. The simple pendulum (see Fig. 1) very nearly moves with Simple Harmonic Motion when the arc AB of the swing is small, or when the string AC is long, so that the path AB of the ball of the pendulum differs little from a straight line. In this case, half the length AB is the *amplitude* of the swing.

The *period* of a Simple Harmonic Motion is the time of a complete swing backwards and forwards: or more precisely, the time which elapses between the passage of the moving body through one particular point, and its next passage in the *same* direction through that point. Thus, in Fig. 3 the period is the time it takes for the ball to move right round the circle, *e.g.* from C to C again, which in the Simple Harmonic Motion corresponds to the interval of time between two consecutive passages through Q in the direction EW.

The *phase* of the moving particle at any particular instant is the fraction of a *period* that has elapsed since it last passed through the central point in the positive direction. Thus in Fig. 3, if we take the instant that the particle appears to pass through O in the direction WE as the point of time to measure from, then when it passes through A its phase will be a quarter of a period; when it passes through Q in the direction EW its phase will be $\frac{5}{8}$ of a period, and so on.

Composition of a Simple Harmonic Motion with Uniform

Rectilinear Motion.—If we replace the ball of the pendulum (Fig. 1) by a funnel with a narrow outlet carrying sand, the pendulum will leave its trace on the table below it in the form of a deposit of sand in a straight line. The sand will be thickest at the ends of the line where the pendulum is moving most slowly. If now we make the whole pendulum with its support move uniformly in a straight line at right angles to the plane of the swing; or, what comes to the same thing, and is more

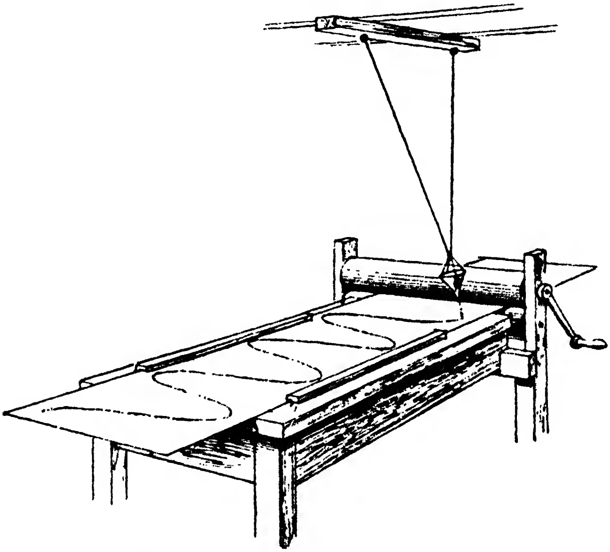


Fig. 4.—Curve of sines. Pendulum with sand.

easily carried out, if we slide a board along underneath the pendulum uniformly, and at right angles to the plane of the swing, the sand will be deposited on the board in a wavy line, which is very approximately what is known as the curve of sines (see Fig. 4).

Vibrations of a Rod.—Take a straight steel spring, or a uniform strip of pinewood, and fasten one end in a vice. Now pull the other end aside and let it go. The spring will vibrate and the motion of each part of it will be harmonic, as that of the

pendulum, though more rapid, *i.e.* of a smaller period. That the motion is harmonic can be shown by fastening a small camel's hair brush dipped in ink to the free end of the spring, so as just to touch a strip of cardboard. Then set the spring vibrating, and draw the cardboard rapidly and uniformly along in the direction of the length of the spring, and the brush traces out a simple harmonic curve.

AOA_1 is the path of a particle moving in Simple Harmonic Motion. OD, DC, CB, BA, etc. are the spaces which it describes in intervals of $\frac{1}{16}$ of a period each. Now communicate to the central point O a uniform motion in the direction OX, and let

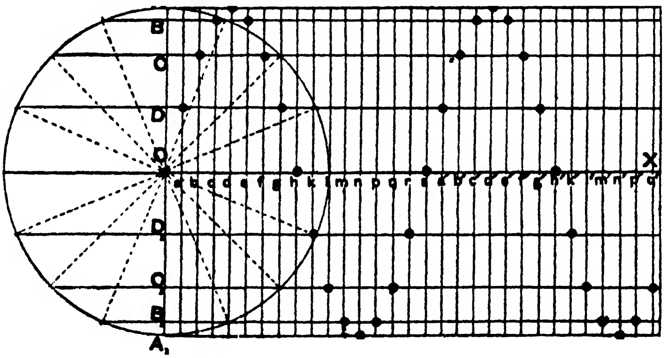


Fig. 5.—Curve of sines

Oa, ab, bc, etc. be the spaces (equal, since the motion is uniform) travelled in intervals of $\frac{1}{16}$ of a period. Then the corresponding positions of the moving particle are given by the dots which all lie on a wavy curve, known as the curve of sines, or Simple Harmonic Curve. It is called the Curve of Sines because the distances Oa, Ob, etc. along the line OX are proportional to the angle described in the corresponding circular motion, while the distances of the moving particle above and below that line are proportional to the *sine* of the angle described.

Notice that if we have a line of particles at O, a, b, c, d, etc., each describing the same Simple Harmonic Motion, but each

particle $\frac{1}{16}$ of a period ahead of the next one in phase, we shall have a wave form of the exact shape of that shown by the dots in Fig. 5, and the wave will move uniformly in the direction OX. The distance (dd′) between the crest of one wave and the crest of the next will be traversed by the wave form in *one complete period.* This distance we call the *wave length.* The time taken in describing this distance is the time each particle takes to make a complete oscillation.

Particles one wave length apart, as, for example, f and f′, are *in the same phase.*

Composition of two Simple Harmonic Motions.—If a particle have at the same time two different Simple Harmonic Motions we can find the resulting motion. To take a few simple cases first :—

1. When the two motions are in the same direction, in the same phase, and of the same amplitude, the resulting motion will be a Simple Harmonic Motion of double amplitude.

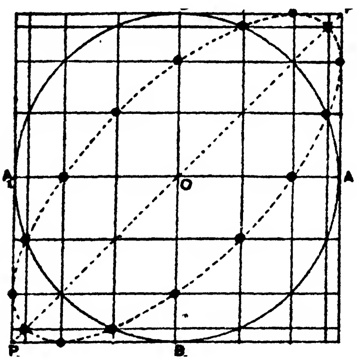


Fig. 6.
Composition of two simple harmonic motions.

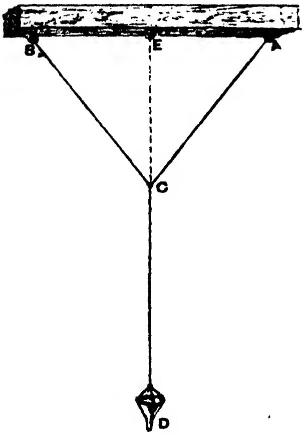
2. When the motions are in the same straight line and of the same amplitude, but differing in phase by half a period, the result will be rest. Thus, in Fig. 6, if one motion alone would cause the particle to be at A and the other motion alone at A_1, the result would be rest at the point O.

3. When the motions are of the same amplitude and phase, but at right angles to one another as AOA_1, BOB_1, the resulting motion will be in the line POP_1.

4. When the motions are at right angles and differ in phase by $\frac{1}{4}$ period, the result will be circular motion. Thus if one motion is at its greatest elongation A while the other is at its mean position, the particle will move in the circle ABA_1B_1.

5. If the motions differ in phase by some other fraction of a period, say $\frac{1}{8}$, the resulting motion will be elliptical, shown in Fig. 6 by the dotted curve.

Composition of Simple Harmonic Motions of Different Periods.—This can be done very effectively by means of a compound pendulum, such as is shown in Fig. 7. The two strings AC, BC are of equal length, and from C a single string supports the weight D. Now, if the weight be pulled aside in the plane ABC, it will swing about the point C so long as AC and BC



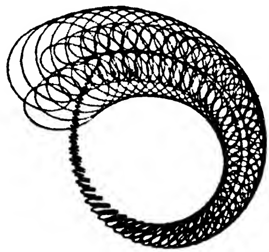


Fig. 7.- Compound pendulum and curve described.

remain tight. But if the weight be pulled aside out of the plane ABC (*i.e.* the plane of the paper) and perpendicular to it, it will swing about the line AB, and the time of its swing will be as if it were suspended by a single string DE. Now if the weight be pulled aside obliquely, it will have two swings of different periods, depending on the lengths DC and DE. The period of the swing of a simple pendulum is proportional to the square root of the length of the string; so if we arrange that DE = 4DC, one of the periods will be double that of the other. Now if the weight be a funnel filled with fine sand, as in Fig. 4, the sand will be deposited in a parabola in this case. The two swings can be

adjusted in any ratio, each change resulting in a different curve. An ingenious form of compound pendulum has been devised by Mr. Goold; there is a single point of support, and the pendulum itself carries a flat board, on which a piece of paper or card-board can be stretched. Beneath the board is suspended another weight, whose distance from the board can be adjusted. Instead of carrying sand, the paper on the board swings underneath a fine pen balanced on a side table so as to be always in gentle contact with the paper. In this way a permanent record can be obtained of the beautiful curves described in the complex swings of the instrument. A reproduction of one of these curves is given in Fig. 7.

Wave Curve, the Composition of two Simple Harmonic Curves.—We have shown in Fig. 5 the curve produced by com-

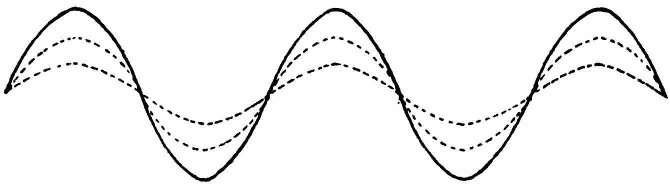


Fig. 8α.—Superposition of two waves in the same phase.

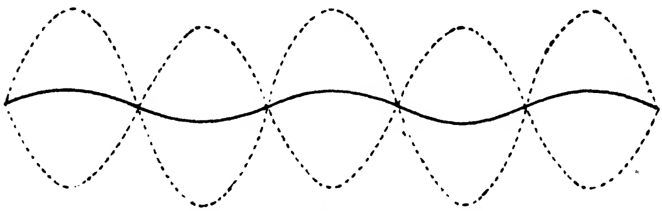


Fig. 8β.—Superposition of two waves in opposite phases.

pounding a Simple-Harmonic Motion with a uniform motion in a straight line. The same construction will help us to see the effect of two Simple Harmonic Motions impressed at the same time on the same particle.

Two Simple Harmonic Motions of the same period and phase, but of different amplitude, give wave forms represented by the

dotted curves in Fig. 8 *a*. The resulting motion will be represented by the plain line, in which the displacement at any point is the sum of the other two displacements. When the two motions differ in phase by a half period, the resulting motion will give a curve whose displacement at any point is also the algebraic sum of the two component displacements (Fig. 8 β).

In Fig. 9 the two thin lines AB and AC show the curves representing two Simple Harmonic Motions of different period, the periods being in the ratio of 2 to 3. They start in the same phase at A, and, after two of the longer or three of the shorter waves, they are in the same phase again. The dark line gives the resulting motion (see SOUND, p. 493).

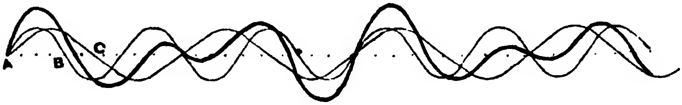


Fig. 9. - Two simple harmonic motions.

Vibrations of a System of Particles—Wave Motion.—It was mentioned on p. 428 that where we have a system of particles in a line at equal distances, and each particle describes a Simple Harmonic Motion, but each particle is a fixed distance ahead of the next, the result will be that a wave form, a Simple Harmonic Curve, will appear to move steadily along. Also, if each particle performs one of these composite movements that we have been considering, the wave form will be the corresponding complicated curve and will appear to move steadily along in the direction of the line of particles.

Waves in Water.—Suppose we have a string of particles, each describing a circle uniformly and in the same direction, but each particle 30° ahead of the next. The positions of the particles are shown in Fig. 10. Notice that the radius in each circle is 30° further round than in the next. The phases then differ by $\frac{1}{12}$ of a period $\left(\frac{360^\circ}{30^\circ}=12\right)$. The wave form is shown by the dotted curve and travels from left to right as the particles move round in their circles. Notice also that the crest

and trough are not of the same size and shape, as in the case of the Simple Harmonic Curve, but that the crests are narrow and the troughs broad. This is what we notice in the case of waves in water, and corresponds with the facts noted on p. 422.

If the circles described by each particle are made larger, the crests will be made narrower still; and in the case of water waves, we shall have the crests breaking into foam if the circle is sufficiently increased.

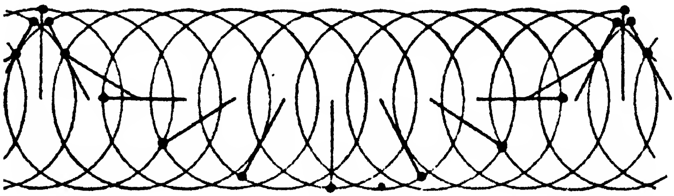


Fig. 10.—Circular motion. Resulting wave-form.

Fourier's Theorem — Resolution of Complex Periodic Motions.—We have dwelt at some length on Simple Harmonic Motions and the methods in which they may be compounded, and have seen the great variety and complexity in the resulting periodic motions. Conversely it can be shown, and has been shown by Fourier, that any complex periodic motion can be split up into a definite number of Simple Harmonic Motions. To take a simple and important case, the converse of proposition (3) on p. 428 tells us that any Simple Harmonic Motion can be split up into two at right angles to each other.

CHAPTER II

Waves

System of Particles connected with each other—Jerking a Rope—Velocity of Wave—Transverse and Longitudinal Vibrations—Waves of Compression—Graphic Mode of Representing them—Circular Waves—Primary and Secondary Waves—Spherical Waves—Plane Waves—Reflection and Refraction—Energy of Wave Motion—Interference—Rectilinear Propagation of Waves—Wave Passing through Aperture—Notion of Rays—Fermat's Law of Least Time.

System of Particles connected with one another—A Rope.—To return to the case of a rope lying on the ground. Jerk one end of the rope. The end of the rope being displaced carries after it the portion of rope next to it. This in turn affects the next, and thus we have the whole length of the rope affected by the simple jerk given to one end; but not all at once, for the rope is not rigid and inextensible, and the transmission of the action requires a certain amount of time. If the rope possesses uniformity in weight, thickness, and elasticity throughout, the action will be transmitted at a uniform rate throughout. The accompanying figure (11) will give some idea of the nature of the motion. AB is a string of particles connected by elastic bands. In (1) they are at rest. In (2) a jerk has been given to A, and by the time it has reached its greatest displacement, the jerk has been transmitted along the string as far as C. In (3) C has reached its greatest displacement or elongation, but now A has returned to its original position, and the disturbance has just reached D. If only one jerk is given to A we have only

a solitary wave transmitted along the string; but if A has imparted to it a succession of jerks or a Simple Harmonic Motion, we have a series of complete waves transmitted along the string, as shown in (4).

Velocity of Propagation.—It should be again noted that the time taken by one particle, say A, to make one complete swing coincides exactly with the time taken for the movement to be transmitted one complete wave-length along the string. Now, suppose the connection between the particles in Fig. 11 to be such that each is always the same fraction of a period behind its predecessor, *e.g.* suppose D to be always a half wave-length behind A. Then the wave will always have the same shape, no

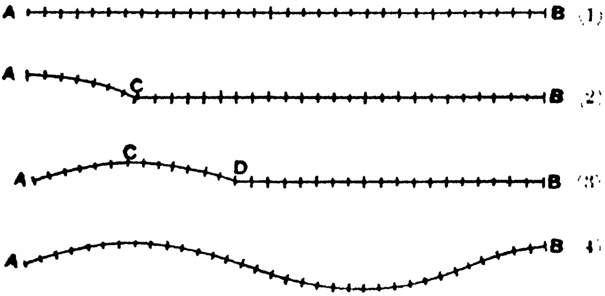


Fig. 11.—Wave travelling along a rope.

matter how fast A moves. If A moves twice as fast, the shape of the wave will be the same, but the wave will be transmitted twice as fast. On the other hand, if the connection between the particles is dependent merely on the distance between them, then if A moves twice as fast, A will be back in its old position by the time the disturbance has reached C, and the wave-length will be half what it was, though the velocity of propagation will remain the same.

Transverse Vibration.—In the case we have just been considering, the wave was transmitted along the string of particles, while each particle vibrated in a direction at right angles to the string. Such vibrations are said to be *transverse* to the direction

of propagation of the wave. The vibrations of the medium which transmits light are believed to be transverse to the direction of propagation of the light.

Longitudinal Vibrations.—Take a number of glass marbles, or billiard balls, and place them in contact in a groove (Fig. 12). Roll the end one A up against B. Instantly, to all appearance, the shock will be transmitted, and the ball at the other end will start off by itself. What happens? The balls possess elasticity of shape, that is to say, when knocked out of shape they return to their original shape again. B is momentarily compressed into the form shown by the dotted line in Fig. 12*a*; it then recovers itself, and in so doing compresses C, which in turn recovers and transmits the compression to D, and so on. In this way a wave of compression travels along the balls and the line of compression coincides with the line in which the

Fig. 12.—Row of elastic balls. Wave of compression. 12 *a*.

wave is propagated, *i.e.* the line joining the centres of the balls. The motion is not instantaneous; for each ball takes time to be compressed and to recover itself, and the velocity of propagation can be measured: but the velocity is great compared with the velocity with which A rolled up against B. This can easily be shown by having a second groove alongside the groove containing the row of balls in contact, the second groove to be clear. Start two balls simultaneously at the same pace, one along each groove, and note that the ball H will start with the shock long before the ball in the clear groove has come up level with the position originally occupied by H.

Waves of Compression and Rarefaction.—*Longitudinal Vibrations continued.*—Fig. 13 (*a*) represents a row of particles which possess elasticity of volume. By this we mean that force is necessary to bring any two closer together, and that when two are brought closer together they display a tendency to

return to their original positions. Now push the end particle up against its neighbour; a resistance will be offered, and it will be forced back again. If the push is repeated at regular intervals, the first particle will vibrate in the line of the push about its original position. But since action and reaction are equal and opposite, the first particle has pushed on the second at the same time that it was pushed back by the second, and so the push has been transmitted down the line, and we have a state of things shown in Fig. 13 (β). In the regions marked P, the particles are jostling closer together. These are the regions of compression. In the regions marked R, the particles are farther apart than ordinary, and these are the regions of rarefaction. The distance

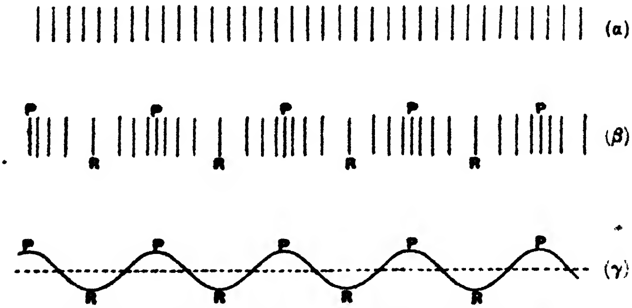
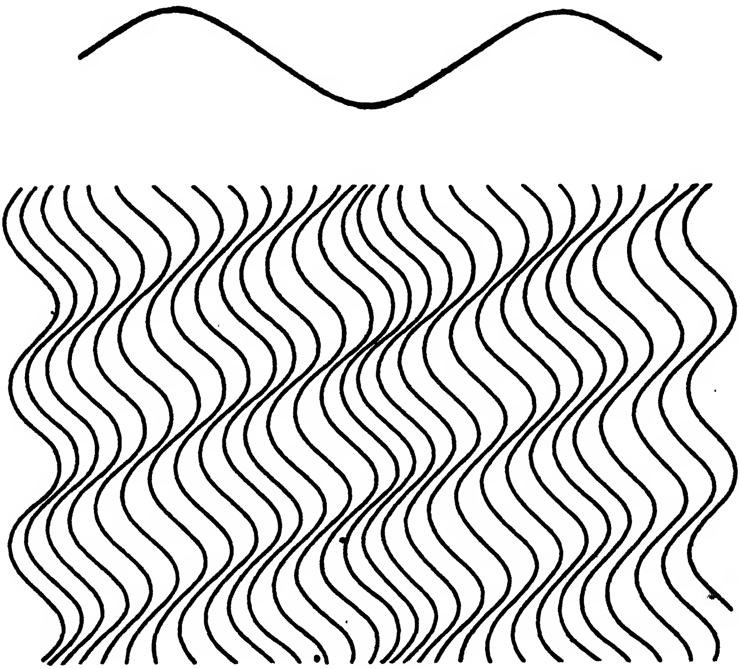


Fig. 13.—Graphical method of representing waves of compression.

PP is one wave-length, and the disturbance travels one wave-length in the time taken by each particle to oscillate about its mean position. The vibrations being in the line of propagation of the waves, instead of across it, are said to be *longitudinal*.

Graphic Method of Representing Longitudinal Waves.—To represent wave motion in which the vibrations are longitudinal by means of a figure, it is possible to draw a series of dots or lines close together in the regions of greatest compression and far apart in the regions of greatest rarefaction, the closeness of the dots or lines being a measure of the compression at each part (Fig. 13) (β). Such figures are troublesome to draw, and even if correctly drawn give to the eye an inadequate idea of the different

degrees of compression. We therefore make use of a wavy line as with transverse vibrations, the distance of any point of the curve above or below the mean straight line being a measure of the degree of compression or rarefaction at that point. Thus in Fig. 13 (γ) the wavy line typifies the motion shown



β

Fig. 14.—Transverse and longitudinal waves.

in 13 (β), the parts of the curve above the dotted line corresponding to regions of compression, and those below to regions of rarefaction.

It is important that the student should observe for himself the actual progress of wave forms, both transverse and longitudinal. Let him cut in the edge of a sheet of paper a number

of very narrow slits, say an inch long and the eighth of an inch apart, and lay the fringe so obtained over a thick wavy line such as that shown in Fig. 14 (a) Wherever a slit crosses this line a black dot will appear. Now let the wavy line be drawn from left to right under the fringe of slits. Each black dot will move

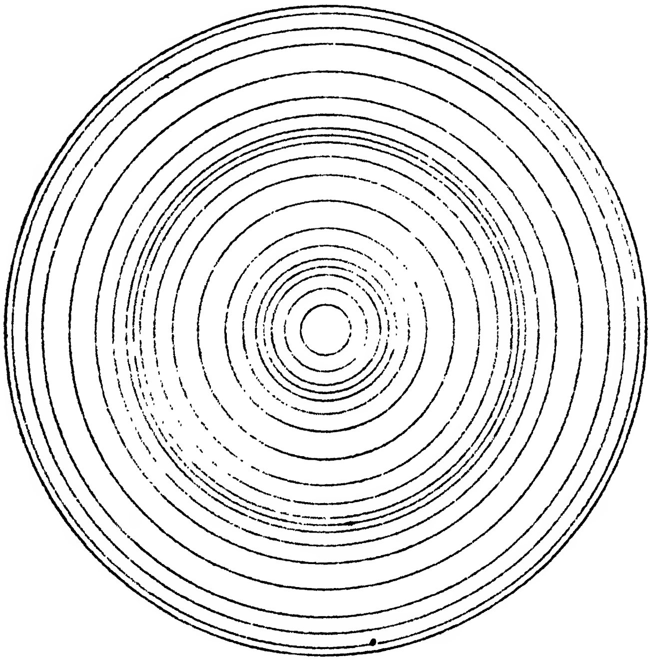


Fig. 15.—Circular Waves.

up and down in its place, while the wave form moves steadily from left to right. The movements of the particles represented by the black dots are *transverse* to the line of propagation of the wave. The progress of a wave of compression may be observed by means of Fig. 14 (β). Cut a narrow slit four inches long in a piece of paper, and lay the slit across the bottom of the figure. A row of black dots will be visible through the slit. Now slide

the book downwards underneath the slit, so that the line of the slit travels up the page. The regions of compression and rarefaction will travel along the slit from left to right; but if the eye is fixed on one particular dot, its motion will be seen to be a simple vibration from side to side in the line of the slit. Such is the nature of *longitudinal* vibration.

Circular Waves.—When a wave travels along a string of particles, each particle transmits some of its energy to the next. But when a stone is dropped into a pool, the disturbed portion of the surface has water all round it to receive the energy, and there being no reason why the disturbance should travel more quickly in one direction than in another, we find that the disturbance reaches all points on the surface at the same distance from where the stone fell at the same time. In other words, the waves are circular (Fig. 15).

Primary and Secondary Waves.—*Huyghens' principle.*—When the disturbance reaches any point on the surface of the pond, that point being disturbed transmits its disturbance to its neighbours. But it has neighbours all round it. Therefore it in turn becomes a centre of disturbance.

The effect of this is shown in Fig. 16. A disturbance from the central point has reached the inner circle. Each point on that inner circle is now a centre of disturbance, and we have an infinite number of little circles whose nett result is the main outer circle which they all touch. The big circles are the primary waves and the little ones secondary waves. It will be noticed that we have not drawn the whole of the secondary

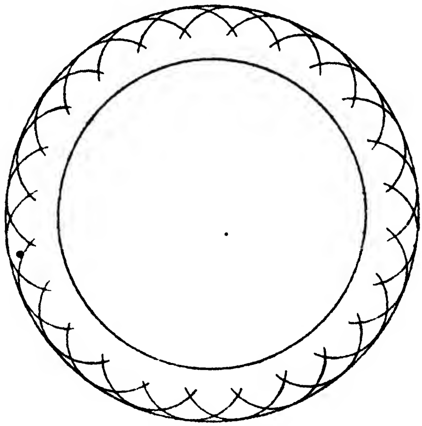


Fig. 16.—Secondary waves.

circles, but only arcs. Are then no secondary disturbances transmitted backwards to the original centre? To make this clear let us return once more to the string of particles. Each particle receives some of the energy of its predecessor and passes it on to its successor. There is no question of which way the wave is to travel. It must be forwards, not backwards. But on the surface of the pond where there are particles all round to receive the disturbance, it is a question which shall get most of it. It might be expected that the particles straight on ahead in the main line from the prime centre would get the most of it; and Professor Stokes has shown that this is the case.

Thus in Fig. 17, B is a point on a primary wave from A, and from B is sent out a secondary wave CDE. The intensity of this secondary disturbance is greatest at C, diminishing according to a fixed law as we get farther from C, and becoming nothing at all at the point E.

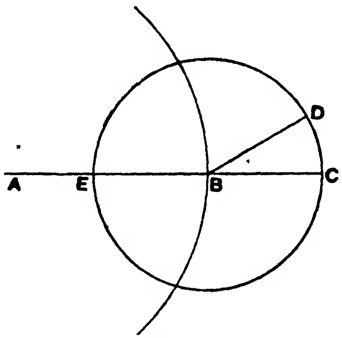


Fig. 17.—Secondary wave.

Spherical Waves.—If instead of the surface of a liquid we take a homogeneous medium, some substance such as air, which has the same properties, the same density, the same elasticity in every direction, above and below, right and left, and imagine a disturbance to be started at some point in this, the waves caused by the disturbance will travel with the same velocity in every direction, and all points at the same distance from the centre of disturbance will be in the same phase at the same instant. In this case the waves are spherical, not merely circular, and every point on a primary spherical wave becomes itself the centre of a secondary spherical disturbance. The law mentioned above about secondary waves (Fig. 17) applies of course to spherical as well as circular waves. In the diagrams which follow, the reader

must remember that the circular waves shown are merely sections of spheres, and that straight lines are sections of planes.

Plane Waves.—When waves come from a very distant source, so that the radius of the spheres to which they belong is

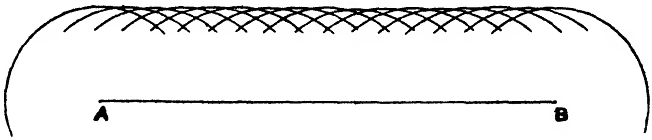


Fig. 18.—Secondary plane waves.

very great, the wave surface may be taken as flat or plane. In Fig. 18 AB represents a plane wave front, and the secondary waves being drawn, it is manifest that the wave front continues to be plane.

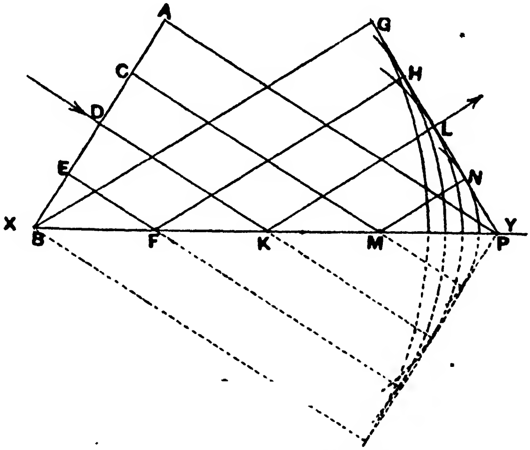


Fig. 19.—Reflection of plane wave.

Reflection of a Plane Wave on a Flat Surface.—AB (Fig. 19) is a plane wave striking on a flat surface XY. B strikes it first, and by the time a secondary wave from A has reached the point P directly in front of A, the secondary wave from B will have a radius BG = AP. Also evidently AP = CM + MN = DK + KL = EF + FH, and the reflected wave has a plane front, GHLNP,

the angle GPB being equal to the angle ABP, by Euc. I. 26. Thus the angle of incidence is equal to the angle of reflection. The dotted portions of the figure show the position the wave front would have reached if the reflecting surface XY had been absent.

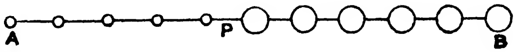


Fig. 20.—Change in density of medium.

Refraction of a Plane Wave.—To return once more to the string of elastic particles, suppose that the particles at some point in the line become suddenly heavier. They will vibrate more slowly, and the wave motion will be propagated more slowly. Thus in Fig. 20 the wave will travel more quickly in AP than in PB.

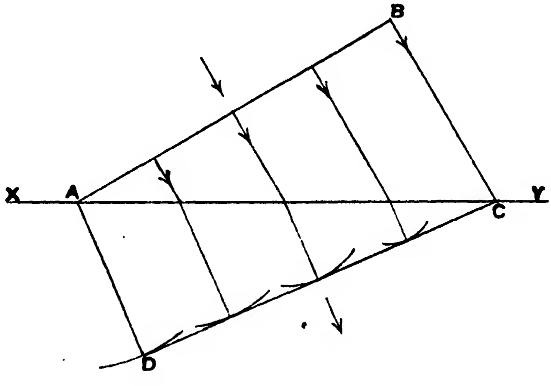


Fig. 21.—Refraction of plane wave.

Now imagine a plane wave in some medium such as air, to strike obliquely on some denser medium such as water, and to continue to be propagated in that denser medium. Let AB (Fig. 21) be the wave front, and XY the surface bounding the two media. In the denser medium the wave will travel more slowly, and the secondary waves will have smaller radii than in the rarer medium.

Hence the wave front in the denser medium will be inclined at a smaller angle to the surface XY, and if V, V′ be the velocities in the rarer and denser media respectively, we have $\frac{AD}{BC}=\frac{V'}{V}$, or since

$$\frac{AD}{AC}=\sin\ ACD, \text{ and } \frac{BC}{AC}=\sin BAC,$$

$$\frac{\sin\ ACD}{\sin\ BAC}=\frac{V'}{V}.$$

Reflection of a Spherical Wave at a Plane Surface.—Spherical waves from the point O are incident on the surface XY. By describing the arcs of the secondary wave at each point on the surface, it will be evident that the reflected wave

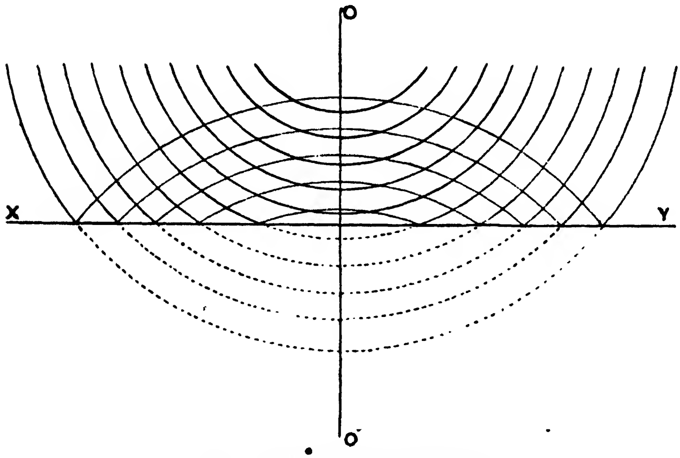


Fig. 22.—Reflection of spherical wave.

fronts are also spherical and appear to come from a point O′ so placed that OO′ is bisected at right angles by XY (Fig. 22).

Refraction of a Spherical Wave at a Plane Surface.—A spherical wave from O strikes a plane surface XY and enters a medium in which it travels with a smaller velocity. The radii of the secondary waves will be all shortened in the same ratio, and the refracted waves will not be spherical but only approximately so, and will appear to come from the point O′ instead of

from O (Fig. 23), O′ being the centre of the sphere which the refracted wave surface most nearly resembles.

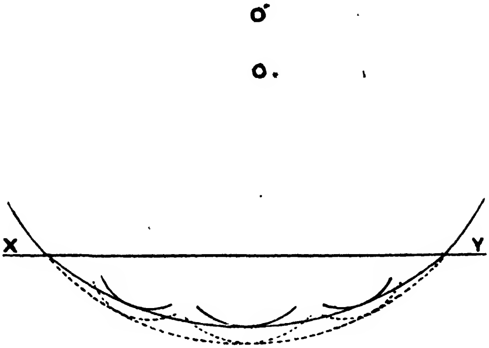


Fig. 23.—Refraction of spherical wave.

Energy of Wave Motion.—When a pendulum is swinging, its energy, or power of doing work, depends on the length of its swing, or on the pace with which it moves through its mean position. When the pendulum is at the end of its swing, it is for one instant at rest, but it still possesses energy by its position. When it is swinging through its lowest point, its position is least favourable, but on the other hand it is moving its fastest (see MECHANICS, p. 40). Its total energy (the energy due to position, or potential energy, and the energy due to motion, or kinetic energy, added together) remains the same. The pendulum may be brought to rest by the resistance of the air; in this case the energy of the pendulum is given to the air partly in the form of heat.

The energy of a Simple Harmonic Motion *is proportional to the square of the amplitude.* Thus, if the amplitude of such a motion be doubled, the energy of the motion will be multiplied by 4.

In wave motion each particle imparts its energy to the next, and if nothing intervenes to change the energy into another form, the energy of each wave remains the same throughout its motion.

When a disturbance is propagated in spherical waves, the radius, and of course the surface of each wave, is continually

increasing, and the same stock of energy has to be distributed over a continually increasing area. In Fig. 24 is shown a small portion ABCD of a wave coming from O. EFGH is the corresponding portion of the wave when its distance from O is doubled. FG is double of BC, and EF of AB; it is evident then that the area EFGH is four times the area ABCD. The energy that sufficed for ABCD will have to suffice for EFGH, and therefore the intensity of the disturbance at any point in EFGH will be $\frac{1}{4}$ of the intensity at a point in ABCD. We find this law then, *that the intensity, or energy per unit area, of a spherical wave varies inversely as the square of the distance from the centre of disturbance.* If the distance be trebled, the intensity will be divided by 9, and so on.

Note that as the energy is proportional to the square of the amplitude, and inversely proportional to the square of the

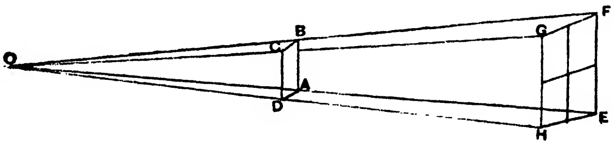


Fig. 24.—Law of inverse squares.

distance, the amplitude of vibration will be inversely proportional to the distance; that is to say, when the distance is doubled the amplitude of vibration will be halved, etc.

Interference.—Let us go back to the pool and drop two stones in at the same instant at two points of the surface not very far from each other. We shall then have two sets of circles spreading from the two centres. What happens when a circle from one centre meets and crosses a circle from the other? Where the two crests meet there is a double elevation of the surface of the water, and where two troughs meet, there is a doubly deep trough. But where the hollow of one wave crosses the crest of the other, the two opposite effects neutralise each other, and the surface of the water is neither raised nor lowered. There is then a patchwork of crests and hollows and neutral

spaces. This effect can be well observed in a flat dish containing quicksilver, the two disturbances being made by striking the surface with two needle points at the same instant.

Fig. 25 is a reproduction of one of a set of photographs of ripples on mercury taken by Mr. J. H. Vincent, of the Royal College of Science, who has kindly allowed the original negative to be used for this picture. The two centres of disturbance

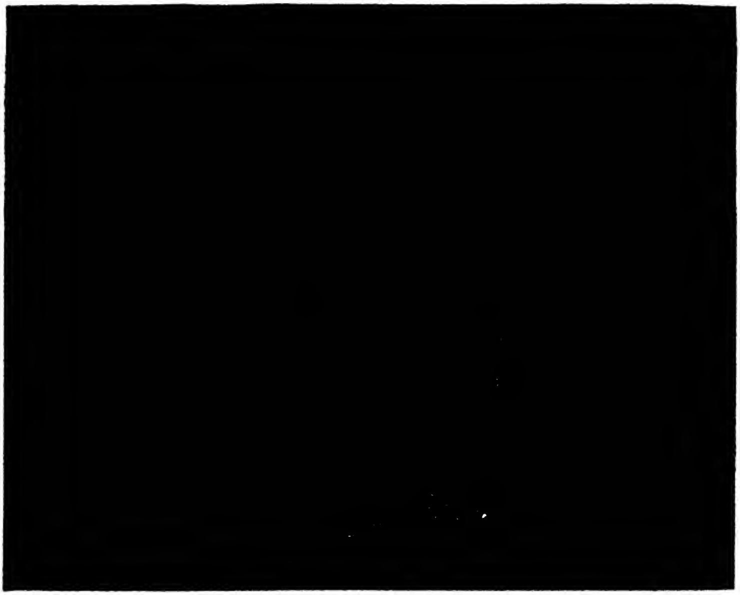


Fig. 25.—Interference of waves.

were two needle points, attached to the same prong of a tuning fork which vibrated 256 times a second, striking the surface of the mercury simultaneously. The two sets of circular waves (or ripples, as Professor Boys calls them) are therefore exactly alike. Where crest meets crest, and hollow meets hollow, they re-enforce each other, and these regions of greatest disturbance are shown in the picture by the dark hyperbolic fringes. The light fringes show the regions of least disturbance, where the crests

from one source meet and neutralise the hollows from the other. The same hyperbolas can of course be obtained by drawing with compasses two sets of circles, alternately plain and dotted to represent waves and hollows, and joining their points of intersection. The result will be a figure like that on the back of a watch, usually called 'engine turning.' Nature's picture is, however, far more beautiful. The ripples are far too rapid to be seen by the unaided eye. The photograph was taken by the light of an electric spark. Other photographs, taken by Mr. Vincent at Professor Boys' suggestion, illustrate the reflection, interference, and diffraction of plane and circular waves. The photographs are $\frac{9}{10}$ of actual size.

This principle of interference applies to all cases in which similar sets of waves are sent out from two or more different sources. The effect produced at any point will be the algebraic sum of the effects of each wave separately. Imagine a point P whose distances from the two centres of disturbance, A and B, differ by one wave length. Thus in Fig. 26, BC is one wave-length. It follows that waves from A and B will reach P in the same phase, crests coinciding and hollows coinciding, or in the case of longitudinal vibrations a compression from A arriving simultaneously with a compression from B, so that the combined effect will be greater than that of a single wave. At another point where the distances differ by half a wave-length, or an odd number of half wave-lengths, the two effects will neutralise each other. There a crest or a compression from A arrives simultaneously with a hollow or a rarefaction from B, and the joint effect will be zero, or if the two amplitudes be unequal, the effect will be the difference between them.

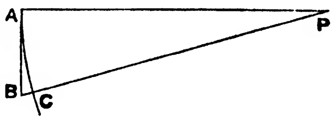


Fig. 26.—Interference of waves.

Rectilinear Propagation of Wave Effects.—Imagine a wave surface advancing towards a point P, and let the centre of disturbance be so far off, compared with the distance of the surface from P, that we may regard the portion of the surface in the

neighbourhood of P as plane instead of spherical. We know that every point in the plane wave sends secondary waves to P, and it is our concern to find which portion of the wave has the most effect upon P. Draw PA perpendicular to the plane of the wave. Let $PA = a$ and let λ be a complete wave length. With centre P and radius $a + \frac{1}{2}\lambda$ describe a sphere. This will cut the plane wave in a circle whose centre is at A. With the same centre P draw spheres with radii $a + \lambda$, $a + \frac{3}{2}\lambda$, $a + 2\lambda$, $a + \frac{5}{2}\lambda$, etc., all cutting the plane wave in concentric circles. Fig. 27 (a) shows a section of this through the line AP, while

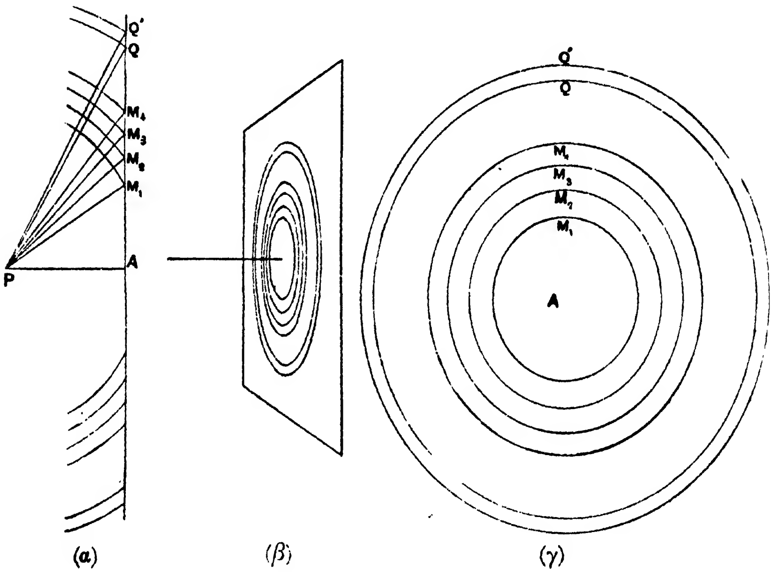


Fig. 27.—Rectilinear propagation of waves.

Fig. 27 (β) shows it in perspective, and Fig. 27 (γ) shows the series of concentric rings on the plane wave. Now by Euc. I. 47,

$$PM_1^2 = PA^2 + AM_1^2$$

$$\therefore \quad AM_1 = \sqrt{PM_1^2 - PA^2}$$

$$= \sqrt{(a + \frac{1}{2}\lambda)^2 - a^2} = \sqrt{a\lambda + \frac{1}{4}\lambda^2}.$$

If the wave length λ is small compared with a, we may write $AM_1 = \sqrt{a\lambda}$.

$$\text{Similarly } AM_2 = \sqrt{2a\lambda},\ AM_3 = \sqrt{3a\lambda},\ \ldots\ AM_n = \sqrt{na\lambda}.$$

Therefore the widths of the rings are $\sqrt{a\lambda}$, $\sqrt{a\lambda}(\sqrt{2}-1)$, $\sqrt{a\lambda}(\sqrt{3}-\sqrt{2})$, etc. Each of these rings will send disturbances to P which will be in alternately opposite phases. To find the area of a ring such as QQ' where $PQ = r$. $PQ' - PQ = \frac{1}{2}\lambda$ and the area of the ring is $2\pi\ AQ\,.\,QQ'$. But by similar triangles $\frac{QQ'}{\frac{1}{2}\lambda} = \frac{PQ}{AQ}$,

$$\therefore\ AQ\,.\,QQ' = \tfrac{1}{2}\lambda\,.\,PQ = \tfrac{1}{2}r\lambda.$$
$$\therefore\ \text{the area of the ring} = \pi r\lambda,$$

but the amplitude of the disturbance is proportional to $\frac{1}{r}$ $\therefore$ the effect of any one of these rings on P is equal and opposite in phase to that of the next. This is without allowing for the increasing obliquity of the secondary wave, owing to which its intensity diminishes. As a matter of fact, the total effect of the plane wave upon P is a series $A_1 - A_2 + A_3 - A_4 + \ldots$ in which the higher terms are nearly equal and very small. It may be written thus—

$$\tfrac{1}{2}A_1 + \tfrac{1}{2}(A_1 - A_2) - \tfrac{1}{2}(A_2 - A_3) + \tfrac{1}{2}(A_3 - A_4) - \ldots$$

and it will be seen that practically the total effect on P is half the effect of the first ring, and that the other rings together produce no effect. If the wave-length of the disturbance is very small, the radius of the first circle is also small, and a very small obstacle at A will cut off the effect of the wave from P. In other words, when the wave length is small, 'shadows' are sharp and distinct.

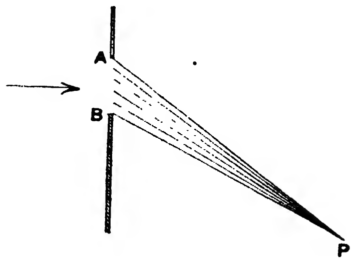


Fig. 28.—Wave passing through aperture.

Wave Passing through an Aperture.—Let a wave moving in the direction of the arrow (Fig. 28) be partly intercepted by

a screen with an aperture AB in it. Every portion of the wave included by AB is the origin of a secondary wave. To find the effect of these on a point P not directly opposite the aperture, the aperture may be divided into sections, the boundaries of which increase in distance from P by half a wave-length. Successive sections will then send waves of opposite phase to the point P. So we find that the total effect at P is that due to the odd portions or remnants at the edges of the aperture which are not included in an even number of these sections. It is evident, then, that in the case of a disturbance with a very small wave length (such as light) the effect of the screen will be to cut off the effects of the wave from all points except those opposite the aperture. If, however, the wave length be large compared with the size of the aperture, the disturbance will be transmitted obliquely. This is the case with sound waves which we know

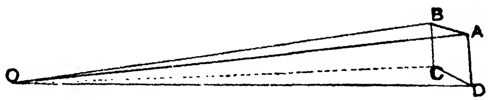


Fig. 29.—Pencil of rays

travel round corners. Sound shadows are, however, very noticeable with large apertures such as a street or a mountain gorge. And, conversely, when light passes through an aperture made so small as to be comparable with the wave-length of light, we have the phenomenon of diffraction.

Rectilinear Propagation and the Notion of Rays.—We have seen from the two preceding articles that disturbances whose wave length is very small throw sharp shadows and do not bend round corners. It is often convenient when considering a small portion of a wave such as ABCD, of which the centre is O (Fig. 29), to regard it as a bundle of straight lines OA, OB, OC, OD, etc., all drawn from O, and each independent of the others. Such lines are called rays, and such a bundle is called a pencil of rays, or simply a pencil.

Fermat's Law—Least Time.—Having formed this notion

of rays, let us consider the particular path chosen by a disturbance in travelling from one point to another. In the case where it travels direct through the same medium all the way, the path is evidently a straight line,—the *ray* in fact being the radius of that particular wave which passes through the second point. The straight line AP is, of course, the shortest possible path from A to P (Fig. 30).

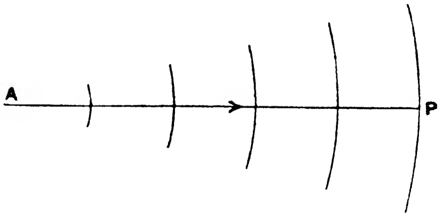


Fig. 30. Path of ray: shortest possible.

Now let the disturbance undergo a reflection at some plane surface XY on its path from A to P.

The reflected waves make the same angle with the surface

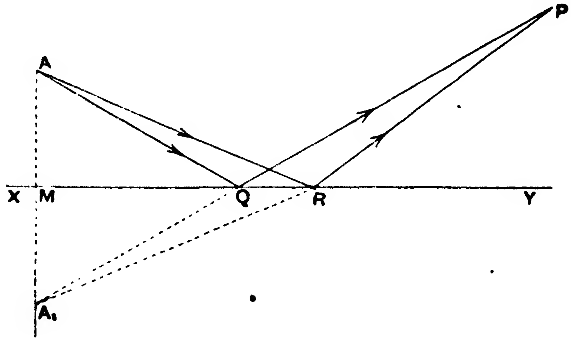


Fig. 31.—Reflection of ray: shortest possible path.

XY as the incident waves (see p. 441), and therefore the angle AQX = PQY. If a point A_1 be taken so that XY bisects AA_1 at right angles (Fig. 31), the point A_1 will be the centre of the reflected waves. Now evidently $AQ = A_1Q$ and $AR = A_1R$. A_1P is shorter than $A_1R + RP$, therefore $AQ + QP$ is shorter than any other possible path as $AR + RP$. In this case the path actually chosen by the *ray* is the shortest possible.

Now, consider a disturbance passing from one medium into another in which it has a different velocity. We know by the law of refraction given on p. 443 that its path will be bent according to a fixed law.

Thus if, as before, A (Fig. 32) be the centre of disturbance, P the point to be reached and XY the surface bounding the two media, the path chosen will be AQ, QP where

$$\frac{\sin AQS}{\sin PQT} = \frac{\text{Velocity in 1st medium}}{\text{Velocity in 2nd medium}},$$

the line ST being perpendicular to the surface at Q.

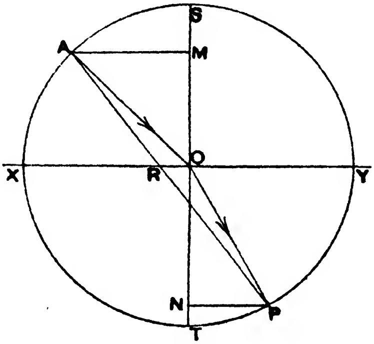


Fig. 32.
Refraction of ray: shortest possible path.

[Or if we draw a circle with centre Q and suppose A and P to both lie on this circle, and draw AM, PN perpendicular to ST, we have

$$\frac{AM}{PN} = \frac{\text{Velocity in 1st medium}}{\text{Velocity in 2nd medium}}\Big].$$

Now it may be shown that the path AQ, QP is traversed by the disturbance in a shorter time than any other possible path, such as AR, RP. The path AQ, QP allows the most advantageous proportion of the time to the quicker medium.

We are now in a position to enunciate *Fermat's Law*, which is that:—The path chosen by a ray joining two points is that which can be travelled over in the least possible time.

SOUND

CHAPTER I

NATURE OF SOUND

How Sound is Transmitted—Velocity of Sound in Air, Water, and other Substances—Intensity of Sound—Reflection of Sound—Echoes—Sound brought to a Focus—Acoustic Clouds—Refraction of Sound—Waves of Compression—Sound a Form of Wave Motion—Comparison of Sound with Light.

SOUND is a disturbance which acts on the sense of hearing. In studying this branch of natural philosophy we have to consider—

(i.) The nature of the disturbance; how sound is produced and how transmitted; vibrations of the air, musical instruments, etc.

(ii.) How the sensation of sound is conveyed to the brain; the mechanism of the ear.

(iii.) Why some sounds are pleasing, and others otherwise.

These three branches belong respectively to physics, physiology, and music, so that, strictly, we are only concerned with the first branch in this book. The others will be only lightly touched upon. They cannot be altogether passed over; for the ear is our chief aid in the study of sound, and music, as we know it, rests on a firm physical basis.

Our first step in investigating the subject will be to discover what is happening when a body is giving forth sound; and a familiar instance can be found by striking a knife sharply

against a tumbler. The ringing sound produced continues until the rim of the tumbler is touched by the finger, when it ceases at once. The sense of touch tells us that the glass *was* vibrating, and as soon as the vibration is stopped the sound ceases. In the same way silence is produced by touching the rim of a sounding bell. We infer that a sound is caused by vibrations in the sounding body.

How Sound is Transmitted.—If a loud-ticking watch is laid on cotton-wool under the receiver of an air-pump, and the

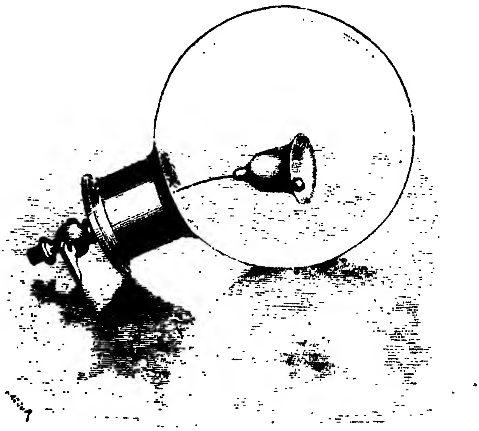


Fig. 1.—Bell in exhausted receiver.

air is pumped out, the sound of the ticking grows fainter and fainter as the exhaustion of the air becomes more complete, and returns to its former loudness when the air is readmitted. Fig. 1 shows a similar experiment with a bell in an exhausted receiver. The stem supporting the bell is flexible and packed with cotton-wool, so that it does not transmit the vibration, and though the hammer is seen hitting the bell, no sound is heard. We infer that some transmitting medium is necessary in order that sound may travel; and this medium is in general the air. A sudden compression or expansion in the air is always accompanied by a sound. Explosions, the popping of corks, the

bursting of paper bags, all furnish instances of this. The air possesses elasticity, and when compressed tends to expand again in every direction ; thus any compression in one region of the air is handed on to the next, and a wave of compression travels through the air, and finally reaches the drum of the ear, whence the sensation of sound is conveyed to the brain.

Velocity of Sound.—When a distant but visible gun is fired, the report reaches the ear not at the same moment that the puff of smoke is seen, but after an appreciable time, the length of the interval being proportional to the distance of the gun. The velocity of sound can easily be calculated from an experiment of this nature, and it is found that the rate at which sound travels in air is about 1120 ft. per second. The velocity increases with the temperature about 2 ft. per second for every degree Centigrade; a rise of temperature increases the air's elasticity by increasing the velocity of the air particles (see PROPERTIES OF MATTER, p. 119).

It may be stated here that the velocity of sound in various gases depends on the elasticity of the gas, and is inversely proportional to the square root of the density. Thus in hydrogen sound travels nearly four times as fast as in air.

That all sounds, high or low, loud or soft, travel at the same rate may be inferred from the fact that a tune played by a distant band reaches the ear unaltered except in intensity.

Newton calculated the velocity of sound in gases on mathematical principles, and obtained the formula $\sqrt{\frac{e}{d}} = v$, where e and d are the elasticity and density of the gas. He found that this formula gave for the velocity of sound in air a value too small by one-sixth of the actual observed velocity. Laplace was the first to explain the discrepancy. Compression of a gas heats it, and rarefaction cools it, and Newton's calculation was made on the assumption that the temperature remained constant. Laplace thought that the heat and cold produced by the rapid alterations of pressure would not have time to pass away, and he made his calculation with this assumption.

The air may be regarded as enclosed in a non-conducting vessel, and the change of pressure corresponding to a given condensation or rarefaction is greater in this case than if the temperature remained constant, as Newton assumed (see Lord Rayleigh's *Sound*, vol. ii.).

Sound transmitted by Solids and Liquids.—All substances possessing elasticity transmit sound. Thus a diver can hear the voices of people on the bank. Fish can hear sounds. By putting the ear to the ground the sound of distant wheels or horses' feet can be heard at a greater distance than in air. Wood is a good transmitter of sound. Put the ear at one end of a stick of timber while another person scratches the other end with a pin, and you will find that the scratching is perfectly audible through the wood, though inaudible at an equal distance in air. A 'pulsion' telephone is easily made; two thin metal or parchment diaphragms stretched over cylindrical mouthpieces are connected by a stretched string or wire. The vibrations caused by a voice at one end are communicated to the diaphragm at that end and transmitted by the string to the diaphragm at the other end.

Velocity of Sound in Water and other Substances.—The historical experiments made in 1827 by MM. Colladon and Sturm in the Lake of Geneva determined the velocity of sound in water. Two boats were moored in the lake at a known distance apart. In one boat was an apparatus by which a bell was struck under water, and at the same instant a flash of light made. In the other boat an observer, with his ear applied to an ear trumpet, the bell of which was under water, noted carefully the interval of time between his seeing the flash and hearing the sound of the struck bell. In this way the value 4708 ft. per second was obtained for the velocity of sound in water.

In solids the velocity of sound is as a rule greater than in liquids, owing to their possessing greater elasticity in proportion to their density. In wood, the velocity is not the same in all directions. Thus in a tree trunk, the velocity is greatest in the direction of the length of the trunk, and greater across the rings

than along them. The difference in the closeness of the wood particles in the different directions is accompanied with a difference of elasticity in those directions. The influence of 'molecular structure' is thus clearly shown. We should expect to find similar differences in crystals which show different properties with respect to heat, light, electricity, etc. in different directions.

The velocity of sound in iron is seventeen times the velocity in air.

Intensity of Sound.—The intensity of a sound diminishes rapidly as the distance of the source of sound increases. It is found that when the passage of the sound is not interfered with by obstructing and reflecting surfaces, the intensity is inversely proportional to the square of the distance (see WAVE MOTION, p. 445). The same amount of motion has to be distributed over an area continually increasing with the square of the distance from the sound-centre.

The intensity of sound diminishes with the density of the air; thus on the top of a mountain the firing of a pistol becomes like the popping of a cork. In cold weather the air is denser, and sounds are heard more plainly. Partly for the same reason, sounds are more plainly heard at night.

Reflection of Sound.—Every one is familiar with *echoes.* Find some wall that gives a good echo, and stand at such a distance from it that you can just hear the last syllable of what you shout distinctly echoed. For this purpose you will have to be at least 100 ft. from the wall. The sound has to travel double this distance, of course, and takes nearly $\frac{1}{5}$ of a second in doing so. The ear cannot hear nor the mouth pronounce distinctly more than five syllables a second. If you retreat to a distance of 220 ft. or thereabouts, you will hear an echo of the last two syllables of your remarks, provided these are made with sufficient loudness.

When there are several reflecting surfaces at different distances from the source of sound or from the hearer, a succession of echoes is heard. This is common in mountain regions. There are many spots in Europe celebrated for the number and

beauty of their echoes. The Gap of Dunloe near Killarney is one of the best known. When echoes follow each other with great rapidity, so as to form a continuous sound, they are called *reverberations*. The firing of a gun in a Scotch glen or even in a small copse is followed by a good illustration of the reverberation of sound.

In large rooms, halls, or churches, the echo or reflection of sound from the walls often makes it difficult to hear distinctly the words of a speaker. The echo may often be deadened by tapestry or hangings of some sort, which are bad reflectors of the sound waves. It frequently happens that a room which when empty has a very bad echo, so that a speaker at one end cannot be distinctly heard by a solitary listener at the other end, becomes free from this defect when filled with an audience, whose persons serve to break up the sound waves reflected from the floor and walls.

Sound brought to a Focus.—Take two conjugate mirrors, as used in radiation experiments (see HEAT, p. 389), and place a watch at the focus of one of the mirrors. Then if the ear, or better, an ear trumpet, which will enable the listener to keep his head out of the way of the sound, be placed at the focus of the other mirror, the ticking of the watch is distinctly heard, although it is inaudible at intermediate points.

Large circular rooms often give curious effects in the way of concentrating sound. In the whispering gallery of Saint Paul's, which is just under the dome, the sound of a voice in one part of the gallery is reflected by the dome and brought to a focus at the opposite side, a whisper being perfectly audible when the speaker and listener are exactly opposite each other. Several other instances are known where buildings act in the same way as the conjugate mirrors mentioned above. Two persons standing at the foci of a long gallery with the walls rounded at each end can converse in whispers which are quite inaudible to persons standing between them.

Acoustic Clouds.—When sound is reflected by an obstacle, the passage of the direct sound is interfered with. Thus

anything that tends to reflect or break up sound tends also to interfere with its direct progress. Unequally heated currents of air have this effect, and Tyndall found that while rain, snow, fog have no appreciable effect on the distance at which sounds can be heard, yet on some perfectly clear days the range of a sound is far less than usual. He describes the atmosphere under such conditions as containing 'acoustic clouds,' layers of air of varying density, which break up the sound waves. Professor Henry attributes the vagaries of distant sounds to refraction, but Lord Rayleigh thinks it probable that refraction

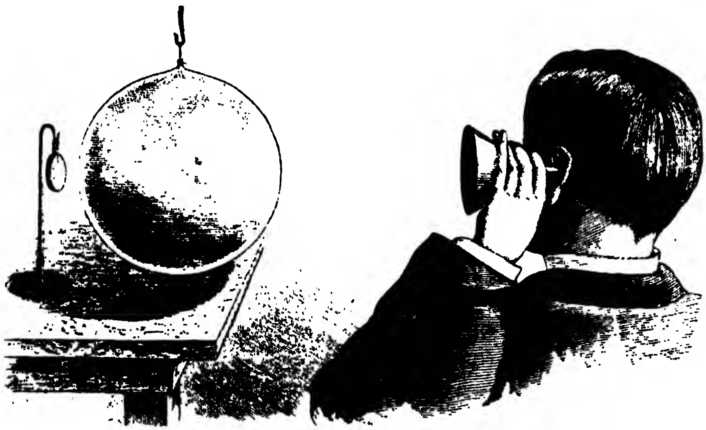


Fig. 2.—Refraction of sound by collodion balloon.

and acoustic clouds "are both concerned in the capricious behaviour of fog signals" (Rayleigh's *Sound*, vol. ii. 2nd edition).

Refraction of Sound.—It has been mentioned that the velocity of sound is less in the denser gases. It is also known that the velocity of light is less in glass, and this is the reason why rays of light are brought to a focus by a lens (see LIGHT, p. 555). Let us see then whether sound waves can be brought to a focus by a 'sound lens.' Fill a collodion balloon with carbon dioxide (carbonic acid gas), and it will be found that the ticking of a watch placed at one point (Fig. 2) can be heard at another point, which is its 'conjugate focus' (see LIGHT, p. 556).

Waves of Compression.—We have already mentioned Newton's calculation of the velocity of sound from the known elasticity of the air, and Laplace's correction of it, which makes it exactly the same as the observed velocity. This is in itself strong evidence that sound in air is a disturbance consisting of alternate compressions and rarefactions. The direct evidence of experience and experiment is no less strong. When a great explosion happens, the windows in the neighbourhood are frequently broken *inwards*. After an explosion at Erith powder mills, by which most of the windows within a radius of some miles were broken, it was found that the windows of Erith church were bent *inwards*, their lead casements having yielded to the outside pressure without the glass breaking much. The windows facing the powder mills did not suffer more than others. Tyndall says: "As the sound wave reached the church it separated right and left, and for a moment the edifice was clasped by a girdle of intensely compressed air, every window in the church, front and back, being bent *inwards*. The bending in of the windows, however, produced but a small condensation of the whole mass of air within the church; the recoil therefore was feeble in comparison with the pressure, and insufficient to undo what the latter had accomplished."

Inferences from the Foregoing Facts.—Sound then travels in waves of alternate compression and rarefaction. Each region of the air in turn vibrates to and fro in the line in which the sound is travelling (*longitudinal vibrations*). The mechanism of waves of compression is explained in WAVE MOTION (p. 435). Their laws of refraction and reflection are the same as those of light (in which the vibrations are *transverse* instead of *longitudinal*). It is interesting to notice the analogies and the differences between sound and light in their ways of travelling. Light travels in straight lines and throws sharp shadows. Sound turns corners. This was Newton's chief difficulty in receiving Huygens' wave theory of light. We know now that the capacity of waves for turning corners depends on the length of the waves. Sound waves are long, and light waves are very short, the comparative

ratio of the lengths of sound and light waves being millions to one. This, as shown on p. 450, is sufficient to explain the difference between their modes of propagation. It may be mentioned again here that light does turn corners (*Diffraction*), and that sound-shadows are known to exist on a large scale. When we climb a hillside and cross a ridge the sound of the water in the glen or combe we are entering becomes suddenly audible. Shrill sounds, whose wave lengths we shall find to be shorter, may be expected to turn corners less easily than deep sounds. Perhaps this is why the hillside, with its facilities for throwing sound-shadows, is considered the most suitable place for bagpipes.

CHAPTER II

Musical Sounds

Musical Sounds Distinguished from Noises—How a Musical Sound is Produced—Pitch and Loudness—The Siren—Relation of Pitch to Rapidity of Vibration—Ratio of Frequencies in Various Intervals—Length of Stretched Strings and Organ Pipes—Resonance.

Distinction between Musical Sounds and Noises.—We have hitherto spoken of sounds of any kind, more particularly perhaps of short sharp sounds, such as the report of a gun. For the report of a gun is a single sound, though it may be prolonged by echoes or reverberations. In considering continuous sounds we are at once forced to notice two distinct classes, which we may call respectively *musical sounds* and *noises*. A musical note is a continuous uniform and pleasing sound, while a noise is an irregular succession of shocks to the ear. The sound of the horn is attractive, while the rattling of stones in a tin kettle is repellent, to dogs as well as to human beings. There exists between musical sound and noise a profound physical difference, apart from the varying emotions of the savage breast occasioned by them.

The ear is so constructed that the effect of a sound dies away very rapidly, but not instantaneously. A sound is a shock given to the drum of the ear by the air. When shocks follow each other with such rapidity that the effect of one is not quite gone before the next comes, the sensation conveyed by the ear to the brain is that of a continuous sound. When the shocks are all alike and follow each other at regular intervals the ear hears a

musical note. If the shocks are irregular, we call what we hear a noise.

Different Ways of Producing Musical Notes.—All that is wanted for a musical sound is a regular succession of shocks following each other with sufficient rapidity. Galileo obtained a musical note by drawing the milled edge of a coin across a knife blade, and he noticed that the more rapidly the minute teeth of the edge of the piastre struck the edge of the knife the higher was the pitch of the note. A stretched string when pulled aside vibrates, and the vibrations follow with absolute regularity, like the swings of a pendulum, only more quickly. Hence the musical note given by pulling a stretched string. If

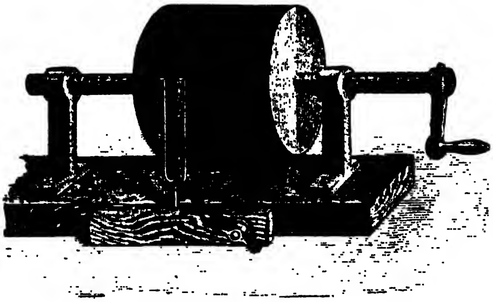


Fig. 3.—Vibrations of tuning-fork recorded.

a toothed wheel be made to rotate, and the edge of a card held against the teeth, the succession of taps which the card receives will, if sufficiently rapid, produce a musical sound, and the more quickly the wheel is turned the higher the pitch of that sound. Take any straight tube open at one or both ends and blow across the edge at one end. The column of air in the tube can thus be set in vibration, and a musical tone produced, the longer the tube the deeper the tone.

Pitch and Loudness.—The note of a tuning-fork depends on the rapidity with which the prongs of the fork vibrate. It is possible to show that the vibrations of a tuning-fork are like those of a pendulum, only quicker. Attach a bristle to one of the prongs by means of a small piece of wax, fix the fork firmly

by a vice in a horizontal position with the end of the bristle just touching a cylinder of smoked glass (see Fig. 3). Now make the fork vibrate by drawing a violin bow across it, and the bristle moves backwards and forwards and clears a small line in the smoked glass. Revolve the glass cylinder quickly but steadily, and the track of the bristle becomes a wavy curve, similar to the curve traced by a pendulum depositing sand upon a board drawn steadily across its line of swing (see WAVE MOTION, p. 426).

This experiment is an instructive one, for by it we can tell the number of vibrations per second that corresponds to a particular note by noticing the speed of the revolving barrel. For, supposing the glass to move at the rate of one foot per second, and that we count thirty waves traced by the bristle in one inch, the number of vibrations per second must be $12 \times 30 = 360$. It should be noticed also that the waves continue all of the same length, although their crests and hollows diminish as the vibrations of the fork become smaller. This, with the fact that the note sounded by the fork gets fainter without the slightest alteration in pitch, tells us that the loudness of the sound is dependent only on the *amplitude* or length of swing of the fork, and that the pitch is independent of the loudness, and depends only on the *rate* of vibration. If the rate of vibration be lowered by loading the prongs with lumps of wax, the pitch of the note is also lowered. It is found that when a tuning-fork gives the same note as a violin string, or as an organ pipe, it is because the number of vibrations per second is the same in all three.

The Siren.—A musical note can also be produced by a regular succession of puffs of wind. When a current of air is blown through a tube, and the end of this tube is alternately opened and shut at regular intervals, a musical note is produced. A method of effecting the opening and shutting of the tube sufficiently quickly is shown in Fig. 4. A disc of cardboard has a number of holes cut in it at equal distances along the circumference of a circle. This disc is mounted so that it

can be made to revolve rapidly. A tube through which a current of air is blown is fixed with its mouth very close to the disc exactly opposite one of these holes. When the disc is turned the current of air is stopped until the next hole comes opposite the mouth of the tube, and thus a regular rotation of the disc produces a series of puffs at regular intervals, resulting in a musical note if the rotation be fast enough. This simple form of siren was invented by Seebeck. If the pace at which the disc rotates can be measured it is plain that we can easily calculate the number of puffs per second that corresponds to any note. For this purpose an improved form of siren was

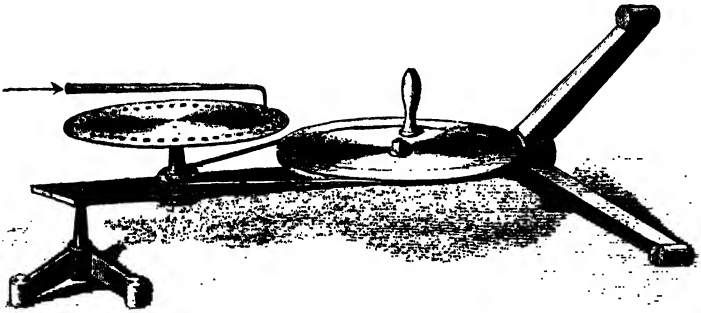


Fig. 4.—Elementary siren.

invented by Cagniard de la Tour, in which the instrument registers its own speed, and in which the current of air which causes the sound causes also the rotation of the disc. The plan of the instrument is briefly this: A current of air can be blown into a pipe A (Fig. 5), which opens into a circular box B, in the top of which is a circular ring of equally spaced holes. A disc CC, which is shown in plan and in section in Fig. 5, has holes exactly corresponding to those in the box, and rotates very close to but not actually touching the top of the box on an axis ED. The axis turns very easily between two steel adjusting screws, and at the top is fashioned into a screw. This turns the toothed wheel F; and the arm

G on the axis of F moves the ratchet wheel H forward one tooth for every revolution of F. In this way the number of revolutions can easily be recorded. Now for the way in which the disc is made to rotate. The holes in the top of the box are oblique, and so are those in the rotating disc, but the latter slant in a direction opposite to the former. Fig. 5 shows sideways as well as frontways a section of a hole in the disc

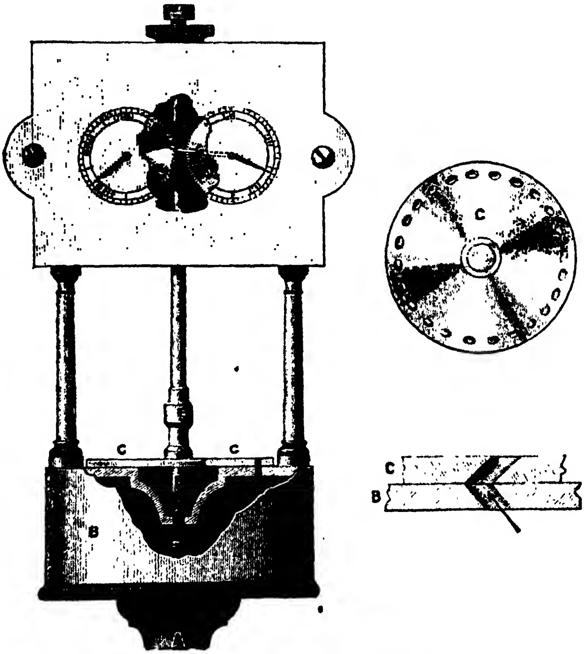


Fig. 5.—Improved siren—Cagniard de la Tour's.

exactly over one of the holes in the top of the box. It is obvious that a current of air in the direction of the arrow will tend to move the disc C to the left. The same thing happening all round the circle of holes, a current of air forced into the box will make the disc C rotate, and so produce the succession of puffs that causes a musical note.

The sirens used in steamers give a low sound, rising rapidly

to an ear-piercing shriek, like that of a beast in pain. This is due to the rapid increase in the speed of rotation as the steam is blown through the instrument. Some of the fog-sirens fitted in lighthouses are rotated mechanically, so as to give fixed notes; and usually two or more different notes, which are distinctive of that particular lighthouse, are sounded at distinctive intervals.

The siren as improved by Dove has four concentric circles of holes, the inner ring containing 8, the next 10, the next 12, and the outer ring 16 holes; it possesses also an arrangement by which any of these may be opened or closed at will. This design is similar to that used in lighthouses for producing the distinctive notes.

Relation of Pitch to Rapidity of Vibration.—Dove's siren can give us much interesting information on the subject of pitch. If we arrange that the circles of 8 and 16 holes shall be open at the same time and sound the siren, we hear two distinct tones, one an *octave* above the other. Increase the speed of rotation and both tones become sharper, but still bear the same relation. Hence we conclude that when one tone is an octave higher than another, the vibrations are exactly twice as rapid in the first as in the second.

We also find that the series of 12 holes gives the *fifth* of the note given by the series of 8 holes. (The interval from C to G on a pianoforte is a 'fifth.')

The series of 16 holes gives the *fourth* of the note given by the series of 12 holes. (The interval C to F or G to C′ is a 'fourth.')

The series of 10 holes gives the *major third* of the note given by the series of 8 holes. (The interval C to E is a 'major third.')

The series of 12 holes gives the *minor third* of the note given by the series of 10 holes. (The interval E to G or A to C′ is a 'minor third.')

We have then this series of relations between the rapidity of vibrations in different intervals.

1 : 2	Octave.
2 : 3	Fifth.
3 : 4	Fourth.
4 : 5	Major third.
5 : 6	Minor third.

The **Pitch Number** or **Frequency** of a note or tone is the number of vibrations per second which make that tone. To find the frequency of any tone of a musical instrument, we have only to sound a tone of the same pitch in our siren, and read off from the recording dial the number of puffs per second by which the tone is produced.

Other methods of determining absolute pitch are given in Lord Rayleigh's *Sound*, vol. i. 2nd ed. pp. 85-90.

Calculation of the Ratios of the Frequency for all Notes of the Scale.—Those who have any acquaintance with the pianoforte will know that the three notes C, E, G form the same chord in the key of C as the notes G, B, D form in the key of G or F, A, C in the key of F. Now the notes C, E, G stand in the ratio of the numbers 4, 5, 6; so a similar relation must hold between G, B, and D and between F, A, and C. A little easy arithmetic gives us the complete series of ratios of the frequencies all up the major scale of C to C′, viz. :—

$$\begin{array}{ccccccccccccccc} C & : & D & : & E & : & F & : & G & : & A & : & B & : & C' \\ 1 & : & \frac{9}{8} & : & \frac{5}{4} & : & \frac{4}{3} & : & \frac{3}{2} & : & \frac{5}{3} & : & \frac{15}{8} & : & 2 \end{array}$$

[or 24 : 27 : 30 : 32 : 36 : 40 : 45 : 48]

(*See* Helmholtz, *Sensations of Tone*).

Pythagoras (B.C. 500) knew the fact that if a string be divided by a bridge into two such parts so as to give two consonant musical tones when struck, the lengths of these parts must be in the ratios of the simple numbers from 1 to 6. The measurements were carefully executed by the Greeks on the monochord (see p. 472), but it was left for Galileo, Newton, Euler, and Bernouilli in the seventeenth and eighteenth centuries to discover the laws of vibration of stretched strings, and the connection between the time of vibration and the length of the string. The connection between simple numbers and musical harmonies was

always regarded as a wonderful mystery, and the notion of Euler that the human mind takes pleasure in simple ratios has been accepted until quite recently as the only possible explanation of this connection. The work of Helmholtz, a *savant* as great in physiology as in physics, has given us at the present day a clearer insight into the subject.

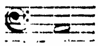
Figs. 9, 20, and 24 are the original pictures in his *Sensations of Tone*.

Length of Stretched Strings and Organ Pipes.—The time of vibration of a stretched string is proportional to the length of the string. For instance, if two strings of the same material and thickness, one 2 ft. long and the other 1 ft. long, be stretched at the same tension, the latter will vibrate twice as quickly as the former, and consequently the tone given by the second will be an octave above that given by the first. Hence also if eight similar strings of equal thickness be stretched at the same tension, so as to give the ordinary major scale, their length must be inversely proportional to the frequencies given above, *i.e.* their lengths must be in the following ratio :—

$$\begin{array}{cccccccc} C & D & E & F & G & A & B & C' \\ 1 : & \frac{8}{9} : & \frac{4}{5} : & \frac{3}{4} : & \frac{2}{3} : & \frac{3}{5} : & \frac{8}{15} : & \frac{1}{2} \end{array}$$

It may be noted that the lengths corresponding to C, E, G form a 'Harmonical Progression.' So do those corresponding to C, D, E and C, G, C'.

The time of vibration of the column of air in an organ pipe is proportional to the length of that pipe.

The note  on the organ is given by a pipe about 4 ft. in length, and the octave above that note is called by organ-builders the 4-ft. octave. The octave below would start from a pipe 8 ft. in length, and the octave above, 2 ft. Below the 8-ft. octave are the 16-ft., 32-ft. and 64-ft. octaves, the last two being found only in very large organs, and giving tones so deep as to be inaudible as musical tones to some ears.

Resonance. — When a tuning-fork is struck and made

to vibrate, it must be held near the ear for its tone to be audible. But if when the fork is struck it is held with its stem on a table, the sound becomes at once audible throughout the room. The vibrations of the fork are communicated to the table, which itself vibrates in time with the fork; a much larger region of the air is set in vibration, and the sound is greatly re-enforced.

The tone of a vibrating string is very faint, unless it is strengthened by a sounding board. When a heavy weight is suspended by a piece of steel pianoforte wire, and the wire plucked aside, the vibrations of the wire are very evident to the eye, but very little sound is audible unless the point of support be connected with something of the nature of a sounding board. The tone of pianos is due to their sounding boards, and in all stringed instruments some sounding apparatus or **resonator** is necessary. In a violin, for instance, the vibration of the strings is communicated by the bridge to the 'belly' of the violin, and from this by means of the sound-post and sides to the back of the instrument. The air within takes up these vibrations, and itself acts as a resonator. The best violins are those in which the wood is most elastic. In a non-elastic substance the vibrations would rapidly die away in friction, and so be converted into heat instead of sound.

We have said that the air inside a violin acts as a resonator. Many other instances of resonating air chambers can be given. Every wind instrument possesses such, and the human voice owes much of its tone to resonating chambers in the bones of the head. A glass tube may be made to re-enforce the tone of a tuning-fork; but the length of the tube must be adapted to the note. Take a glass tube of over an inch diameter and 18 in. long, and hold one end in a vessel of water. Strike the tuning-fork and hold it over the other end of the tube. Lower the tube into the water; when it is at a certain depth the note of the fork sounds loudly. The same result can be obtained by using a tall glass receiver of uniform diameter, and pouring water slowly into it until it re-enforces the sound of the fork held over its mouth.

The outward-swing of the prong A (Fig. 6) compresses the column of air, a wave of compression travels down to the surface of the water at B, is reflected there, and comes back just in time to re-enforce the inward swing of the prongs. It is obvious that if we know the number of vibrations of the fork per second we can find the length of the corresponding sound wave, and the velocity of sound. For suppose the fork to vibrate 250 times in one second, the time of a half-swing is $\frac{1}{500}$ of a second. In this time the wave of condensation goes from A to B and back again.

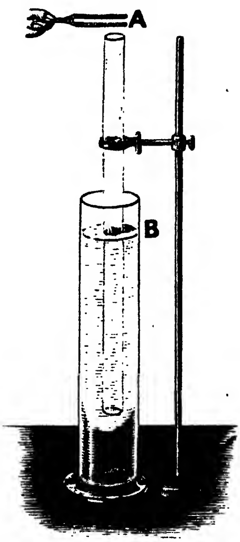


Fig. 6.—Resonance of tall receiver.

The length of the sound waves is therefore four times the distance AB, and the velocity of sound per second is this wave length multiplied by 250,[1] the number of vibrations per second. Or if we know the velocity of sound (say 1120 feet per second) we can from an experiment such as this find roughly the number of vibrations per second of a tuning-fork.

The explanation of the marked effect of sounding boards and resonance chambers is this. The air slips readily out of the way of a small prong or a string. But it finds more difficulty in escaping compression when a large surface is in vibration, and when it is imprisoned in a chamber it cannot slip out of the way, and so must undergo the compression and rarefaction impressed on it by a vibrating fork at the mouth of that chamber. (See also page 478.)

[1] The diameter of the receiver must be taken into consideration, as it is found that a wide tube is equivalent to a narrow tube of greater length. If two-fifths of the diameter of the tube be added to the length, and the result be multiplied by 4, a more correct value of the wave-length will be obtained.

It should be mentioned that resonators, such as the receiver in Fig. 6, resound not only to their own particular tone but to tones of approximately the same pitch. This has been noticed in buildings. We have it on the authority of Sir Walter Parratt that the key of Magdalen College Chapel, Oxford, is nearly G♯, and that when the chaplain intones the prayers upon a pitch slightly sharper than this, the *Amens* seem to die down to the chapel note.

Doppler's Principle. — When a locomotive, sounding its whistle, passes an observer, there is often a notable fall in the pitch, more particularly if the observer is in a train going in the opposite direction. A similar effect has been observed in the sound of a bicycle bell by a cyclist riding in the opposite direction. The fall in pitch occurs at the instant of passing, and is due to the fact that the relative velocity of the two (the source of sound and the observer) is helping to increase the number of waves which reach the ear when the two are approaching each other, while it diminishes the number when they are receding from each other. If the number of waves sent out per second is n, the velocity of sound V, and the relative velocity of the two v, the number of waves reaching the observer in one second will be $\frac{nV}{V-v}$ during approach, and $\frac{nV}{V+v}$ after passing. Doppler was the first to give the explanation, and his "principle" applied to the study of light gives us a means of measuring the rate at which the fixed stars are approaching or receding from us (see page 601).

CHAPTER III

VIBRATIONS OF STRINGS, PLATES, AND PIPES

Monochord—Nodes and Ventral Segments—Harmonics—Chladni's Figures—Organ Pipes, Stopped and Open—Velocity of Sound in Liquids and Gases calculated from Pitch of Sound.

Vibrations of Strings.—The monochord is made, as its name implies, by stretching a single string or pianoforte wire between two fixed points which are fastened to a sounding-board. Fig. 7 shows a monochord as usually arranged. On

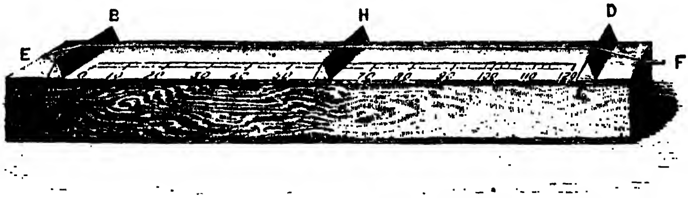


Fig. 7.—Monochord.

this the two fixed points referred to are the points where the string leaves the edges of AB and CD, bridges which stand on the resonating box or sounding board. The ends of the strings are fastened to pegs E and F, by turning which the tension of the string can be altered. Preferably a weight can be hung on at one end of the string, thus affording a means of measuring the tension. There is another movable bridge GH, which can be inserted between the two fixed bridges.

(i.) Pluck the string and observe the tone. Then insert the

movable bridge exactly half way, and again pluck the string. The new tone is the octave of the first, *i.e.* the vibrations are twice as rapid, in other words the frequency (the number of vibrations per second) is doubled.

(ii.) Increase the tension of the wire by screwing one peg up, or by putting on extra weight. The tone becomes sharper.

(iii.) Use a thicker or heavier wire with the same length and tension as before, and the tone is found to be flatter.

From a series of similar experiments, the following laws governing the vibrations of strings may be obtained.

The times of vibration of stretched strings vary—

(1) Directly as the lengths of the strings.

(2) Directly as the square roots of their weights per unit length.

(3) Inversely as the square roots of their tensions.

[The frequency is of course obtained by dividing one second by the time of vibration, and therefore the frequencies vary inversely as (1) and (2) and directly as (3).]

Nodes and Ventral Segments — Harmonics. — When a violin bow is drawn across the monochord a better tone is produced than by simply plucking it. Now put a finger of the left hand on the string exactly one-third of the way along, and draw the bow across with the right hand. The note produced is a twelfth above the note given by the open string, that is to say, if the note of the open string is C, the note when the string is stopped at a point one-third of its length from one end is G′, of which the frequency is three times that of C. The better to see what happens, put some little paper riders at different points along the string and repeat the experiment. The vibrations of the string will dislodge all the riders except those close to the points of trisection of the string. This shows that the string is vibrating in three sections, and the period of these vibrations is, as we should expect, one-third of the period of the whole string. Repeat the experiment, stopping the string with the finger at points one-fourth, one-fifth, one-sixth of its length from the end. The notes heard will be C″, E″, G″, the frequencies of which

are four, five, and six times the frequency of C. The way in which the string vibrates in each case is shown in Fig. 8.

The lowest note given by the open string is called the fundamental tone, and the others are called its harmonics or upper partial tones. The octave (C′) is the first upper partial, and so on. The points at which there is no vibration are called nodes, and the vibrating portions of string between each node and the next are called ventral segments. When the open string is made to sound with the bow, it is possible for a careful listener to hear not only the fundamental tone, but also several of the

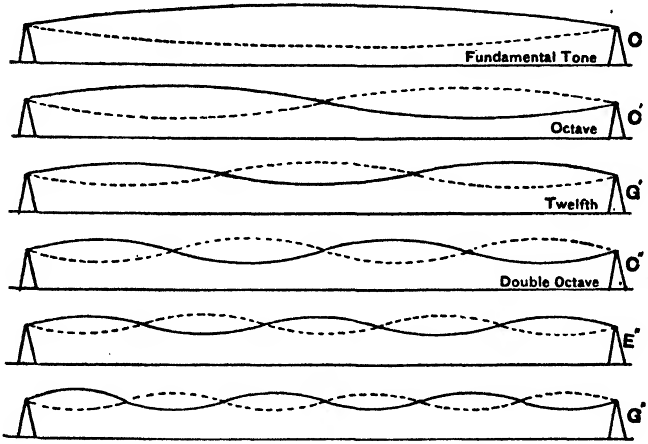


Fig. 8.—Vibrations of a stretched string.

upper partials, showing that the string is vibrating not only as a whole, but also in sections. Strike a note of the piano, and you may hear not only the note itself but also its octave. Helmholtz invented a means by which an unpractised ear can hear the upper partials in a compound tone. He made resonators in the shape of a hollow sphere (Fig. 9), with a little opening at *b* to be applied to the ear, and a larger opening at *a*. These resonators re-enforce one note only, so that if a compound tone produces sound from such a resonator, that compound tone must contain the tone to which the resonator responds, and if a

note on the piano or any instrument contains that particular tone among its upper partials, the ear applied to the resonator will hear that upper partial and that only.

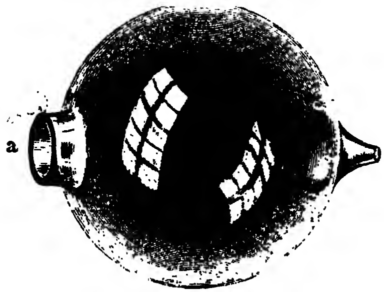


Fig. 9.—Tuned resonator.

The **quality** of a tone depends on the upper partials, and musical instruments are not good for much unless their tones are rich in upper partials. The human voice is particularly well supplied in this respect. It is possible to use the piano itself as a resonator. Hold down the key of the middle C so as to raise the hammer from its wires and leave them free to vibrate. Now strike the C next below sharply and release the key after a little time, still holding down the middle C. The sound of the lower C ceases, but the middle C can be distinctly heard. Its wires have been set in vibration sympathetically by the first upper partial of the lower C. This sympathetic vibration is always produced when one body vibrates in the neighbourhood of another body of the same period. Set an A tuning-fork in vibration and hold it over the open A string of a violin. That the latter is set in vibration can be seen by the displacement of a paper rider put on it. The action is similar to that of pushing a person on a swing. A number of slight pushes given at the right moment soon produce a large swing. Buildings are frequently endangered by sympathetic vibrations set up by machinery at work in them. The danger is lessened by altering the rate of working of the machinery. Stories of bridges and buildings fiddled down by musicians owe whatever substratum of truth they possess to the well-established facts of sympathetic vibrations. Certainly ships may be endangered by meeting with waves on the broadside which have a period equal to their own period of oscillation; if the course be not altered so as to change

the frequency with which the waves are met, the ship will be rolled over.

Vibrations of Plates.—Chladni (died 1827) investigated the vibrations of strings, rods, and plates, and may be regarded as 'the founder of modern acoustics' (Tyndall). His method of making the vibratory motion of plates visible is to sprinkle fine sand over the plate, when held by a clamp at its centre (Fig. 10).

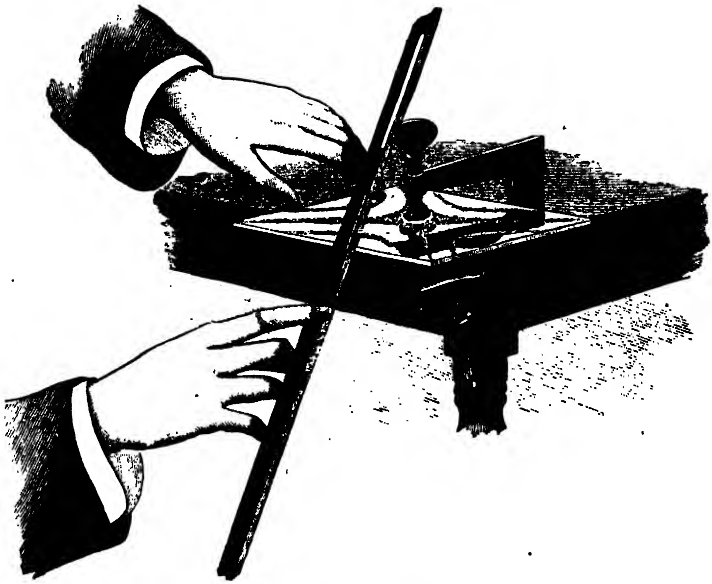


Fig. 10.—Bowing a glass plate.

Then a violin bow is drawn across the edge of the plate and at the same time one or two points on the edge are 'damped,' that is, touched with the finger. The sand at once ranges itself along certain lines in the plate.[1] These are lines of least vibration, stationary or **nodal** lines. The portions of the plate on either side of them are moving alternately up and down, just as the

[1] Savart found that lycopodium and other very fine and light powders behave differently to sand. For an explanation, see Lord Rayleigh's *Sound*, vol. i. 2nd ed. p. 368.

plate, given in section in Fig. 11 α, if damped at the points N and N′, would assume alternately the positions given in Fig. 11 β and 11 γ, the middle part being up when the ends are down, and down when the ends are up. The sand figures alter in the most beautiful and astonishing way as the positions of the damping finger and of the violin bow are changed. Fig. 12 shows the sand figures obtained by damping respectively the middle point of an edge, a corner, and the points of trisection of an edge of a square plate. The regions marked + are above the average level when those marked − are below, and *vice versâ*. For a fuller account of Chladni's figures the reader is referred to Tyndall's *Sound*, and for an account of the rather painful tones emitted by the plates he should consult Helmholtz's *Sensations of Tone*.

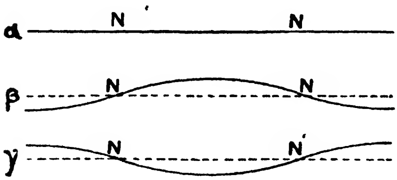


Fig. 11.—Vibrations of glass plate.

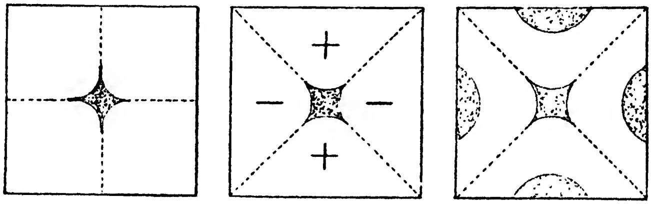


Fig. 12.—Chladni's figures.

Organ Pipes, Flutes, and Flue-Pipes.—On p. 473 a description is given of a column of air made to resound to a tuning-fork. The column of air of the right length re-enforces the particular note given by the tuning-fork. But when we take any column of air contained in a straight tube and make a flutter in the air at one end of the tube, the tube selects from the flutter (which is a confused collection of pulses or vibrations) that particular pulse which suits it and resounds to it, making a musical note. This is the principle of flutes and

organ pipes. The flutter is usually made by forcing a stream of air across a sharp edge at one end of the tube.

Fig. 13 gives a longitudinal section of a stopped wood pipe. The air is driven by the bellows into the air-chamber C. From C it can only escape through the narrow slit *ss*, which directs it against the sharp edge *tt*; the air current passing inside or outside this edge causes either condensation or rarefaction in the pipe, thus starting vibrations in the air column BB, which in their turn control the current. The vibrations of the air in the pipe die away almost at once when the air current ceases. Air, as well as other fluids (p. 131), is viscous, and the energy of sound waves is dissipated in the form of heat. The pipe represented is 'stopped,' that is, a plug is inserted in the top of it, making the top of the pipe a node; its sonorous wave (see p. 473) is four times the length of the column BB, hence its note is an octave deeper than that of an open pipe of the same length. A stopped wooden pipe is often the pipe of the deepest tone in a small organ, as it is possible to get a 16-ft. tone with a pipe 8 ft. long.

Fig. 13.—Stopped diapason—wood.

Fig. 14.—Open diapason—metal.

Fig. 14 represents an open metal pipe, usually made of tin. The arrangements of air chamber, narrow slit and sharp edge are the same as in the wooden pipe (Fig. 13), and, as is partially explained in the next paragraph, the sonorous wave is twice the length of the pipe. The open diapason stop usually seen in the front of an organ consists of metal pipes such as that illustrated in Fig. 14.

Nodes and Loops in Organ Pipes.—In a stopped pipe it is plain that the air at the closed end B (Fig. 15) of the tube is not free to vibrate up and down, so that at the point B we have a *node*, *i.e.* a point where there is no vibration, though great variation in pressure. A, on the other hand, the middle point of a ventral segment, is a point of maximum vibration, sometimes called a *loop*; but the variation in pressure at A is slight. Suppose the air at A to start vibrating upwards. By the time it has come to the end of its upward swing the wave of compression will have reached B, where it is reflected and reaches A again in the middle of A's downward journey. Now the air at B begins to be rarefied, and the maximum of rarefaction at B is reached when the air at A is at the bottom of its downward swing. Thus the air at A executes a complete vibration in the time required for, first, a wave of compression, and then a wave of rarefaction to pass from A to B and back again. Hence the wave length of the fundamental tone of the stopped pipe is four times its length. It is important to note that, when the air at the open end of a pipe is vibrating outwards, a wave of rarefaction travels back into the pipe. In other words, *when a wave of compression reaches the open end of a pipe, it is reflected as a rarefaction.* This should be remembered in looking at Fig. 15 (β), in which the two positions of the dotted line at A correspond to the two extreme positions of the air at A. Compare also Fig. 13 on page 436, and Fig. 8 on page 477. The transverse vibrations of a stretched string travel up to the nodes at the end, which

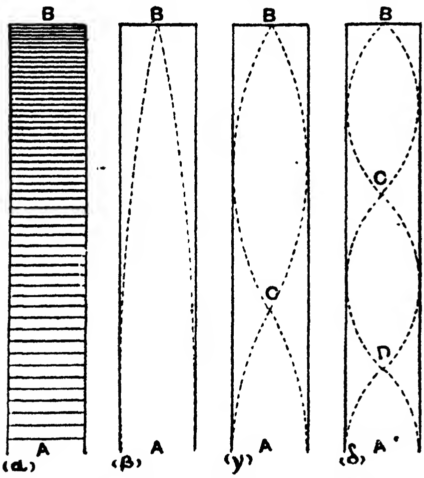
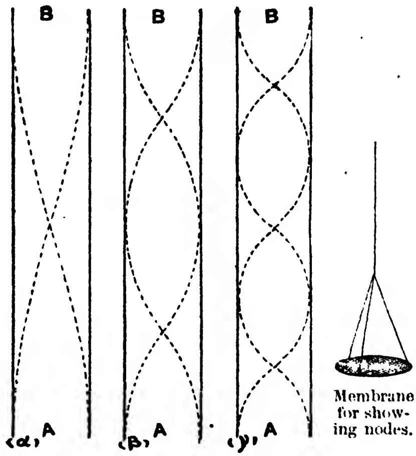


Fig. 15.—Nodes and ventral segments—stopped pipes.

reflect them back like the stopped end of a pipe. Note that *the distance between any node and the next loop is a quarter wave length.* Therefore, of course, the distance between two successive nodes (as in Fig. 8) is a half wave length. And this fact affords a method of measuring the velocity of sound if we know the frequency of the tone emitted. The stopped pipe in Fig. 13 can be converted into an open pipe by removing the plug B (which is movable for purposes of tuning). It is found that the open pipe gives a note approximately an octave higher than a stopped pipe of the same length. This will be realised more clearly on comparing Fig. 16 (α) with Fig. 15 (β). While the wave length is four times that of the stopped pipe, it is only twice that of the open pipe. (See also page 473, footnote.)

To see that there is a node in the middle of an open pipe, it is necessary to have one made with a glass side. In this we can lower by a string a ring with a membrane of thin sheet india-rubber stretched over it, on which a little fine sand is laid. At the mouth of the tube the membrane gives a buzzing sound and the sand jumps about, but as we lower the string, we find a point where the buzzing ceases and the sand is still. This is a node, and is halfway down. Now both the stopped and the open pipes give other tones besides the *fundamental* tone (see page 477). If the current of air is strengthened, higher tones are heard. But these overtones are limited for a stopped pipe by the fact that one end must be a node and the other a loop. If Fig. 15 (γ) and (δ) be examined,



Nodes and ventral segments—open pipes.
Fig. 16.

it will be seen that the upper partial tones must have frequencies which are 3, 5, 7 . . . times that of the fundamental tone. In an open pipe, the nodes are distributed symmetrically (see Fig. 16 (β) and (γ), and the upper partials have frequencies which are 2, 3, 4 . . . times that of the fundamental tone, just as in the case of a stretched string. The positions of the nodes can be determined experimentally as before.

There is an interesting parallel between the 'singing arc' (p. 832) and an organ pipe. The current corresponds to the stream of air and the controlling coil to the volume of air in the pipe; the arc gives the flutter. Or, to take a more familiar illustration, the mainspring of a watch and the weights of a clock supply the energy required to keep them going. The balance-wheel and the pendulum control this supply and give the time to it, and correspond to the resonance coil of the musical arc and the air column of the organ pipe.

Velocity of Sound in Solids, Liquids, and Gases.—When a rod of wood or glass is rubbed, vibrations are started along it, *longitudinal vibrations* we may call them. These are of exactly the same nature as the vibrations of the air in an organ pipe; but they are transmitted with greater speed owing to the greater elasticity of solid substances. A musical tone can be produced by such longitudinal vibrations. On comparing the length of a rod of pine-wood giving a certain note with the length of a column of air in an organ pipe giving the same note, we find that the pine rod is ten times as long as the column of air, and we conclude that the velocity of sound in pine-wood is ten times the velocity of sound in air. Chladni is the inventor of this method of determining the velocity of sound in elastic solids: also by filling organ pipes with different gases and liquids, and comparing them in length with pipes filled with air, giving tones of the same pitch, he was able to calculate the relative velocity of sound in those gases and liquids. For instance, a pipe full of hydrogen giving a certain note is four times as long as a pipe full of oxygen giving the same note. Hence the velocity of sound in hydrogen is four times the velocity of sound in oxygen.

CHAPTER IV

Reed Instruments

Reed Pipes—The Larynx—Vocal Cords—Wood Wind—Brass Instruments.

Reed Pipes.—The principle of reed pipes is the same as that of the siren. Air is driven through a passage where there is a close-fitting door free to open or shut. The opening and shutting of this door breaks the current of air into puffs, and if the opening and shutting follow at regular intervals a musical tone is produced. The door or reed is generally a tongue of metal, which fits closely over the opening through which the air is driven. An harmonium vibrator or reed is shown in Fig. 17. It is capable of vibrating between the two extreme positions

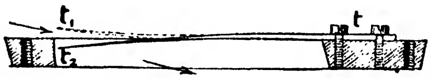


Fig. 17.- Harmonium reed.

tt_1 and tt_2; the arrow shows the direction of the current of air.

The harmonium and the American organ both have a free reed as illustrated, working clear in the slot of the frame of the reed. The reed of the harmonium is, however, worked by *pressure*, the air being forced through by bellows; the reed of an American organ is worked by *suction*. The difference between the two methods may be illustrated by the Jew's harp. When the breath is drawn in, the American organ is illustrated; the tone is less annoying than when the breath is blown out; this

is partly due to the resonance of the mouth. In an American organ a wooden tube is sometimes added after the reed, which modifies the tone in the same way.

Fig. 18 shows a section of a reed pipe in an organ. The free part of the tongue can be lengthened or shortened by means of the movable tuning wire, which presses against the reed or tongue; thus the pitch is lowered or raised, and the pipe brought into tune. The reed may be a 'free reed,' as in Fig. 17, but in most stops English organ-builders employ a 'striking reed,' in which the reed or tongue comes down on the edges of the slot and completely closes the hole; such a reed is shown in Fig. 18, though the 'throw off' of the reed from the tube is exaggerated: it could not be seen otherwise. These are more powerful than free reeds, but there are some stops, such as the *cor anglais*, in which the free reed is more commonly used. The trumpet, oboe, and cornopean are also reed stops.

Fig. 18.
Reed organ pipe—
Vox humana.

Bassoons, oboes, and clarinets are reed instruments; and the human lips in conjunction with brass instruments, as well as the human vocal cords, are further examples of the same thing.

The Larynx.—If a tube of wood is cut in wedge fashion as shown in Fig. 19, and then two strips of sheet india-rubber are stretched on each side, so as to leave a narrow slit running across between the two sharp points of the wedge, an artificial larynx or voice producer is made. The vibrations of the two sheets

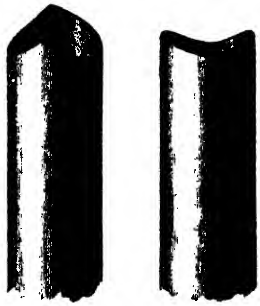
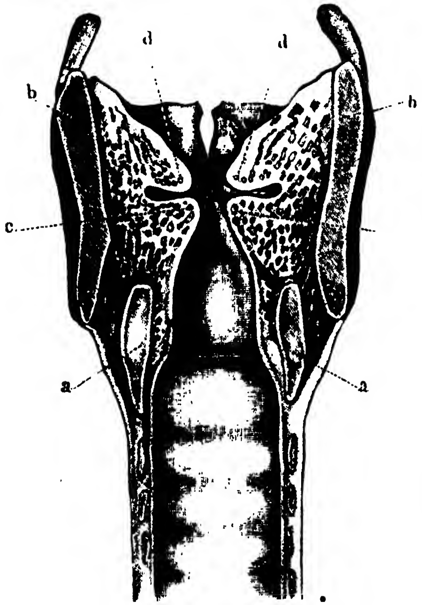
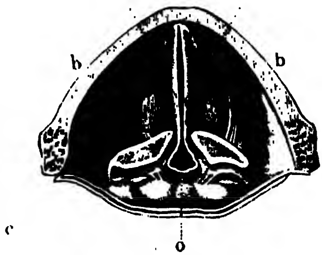


Fig. 19.—Artificial larynx.

of india-rubber, or *membranes*, as we shall call them, open and close the slit and act in the same way as the reeds we have been describing, converting the continuous breath into a succession of puffs. The human *larynx* is an instrument of this kind. The two membranes are called the *vocal cords.* They are stretched across the *trachea* or wind-pipe, leaving between them a small slit called the *glottis.* The length and tension of these





a, Section of ring cartilage.
b, ,, ,, shield cartilage.
c, ,, ,, lower voice membranes } 'vocal
d, Section of upper voice membranes } cords.'
o, Aperture for breathing, which is closed in singing by the stretching of the vocal cords. Between the upper and lower voice membranes can be seen the *ventriculi morgagni.* The figure on the right is the vocal passage seen from above.

Fig. 20.—Human larynx.

vocal cords can be altered with great rapidity; hence the extreme flexibility and great *range of tone*, usually called *compass*, of the human voice. A picture of the larynx is given in Fig. 20. The tightening of the membranes makes their vibrations more rapid, and so raises the pitch. A deep bass note is produced by large slow vibrations of the vocal cords. The perfect voice is one in which the glottis is opened and closed with per-

fect completeness and regularity. The quality of the tones can, however, be greatly varied by altering the shape of the air-chamber inside the mouth and of the mouth itself. The tones of the voice are very rich in upper partials (see p. 478), and the mouth can be altered so as to resound to one or other of these upper partials. It is in this way that the different vowel sounds are produced. The sound *oo* in *moon* is produced when the fundamental tone only is re-enforced. Other vowels contain admixtures of the upper partials in various proportions. It is easy to find out for oneself that the mere altering the shape of the mouth produces the change of vowel sound. Sing (or say) the vowel *ah*, and without altering the note change the sound to *oh*, and then *oo*. You will be conscious of no alteration in the region of the wind-pipe, but you will find that a considerable change has to be made in the shape of the mouth. Helmholtz analysed the vowel sounds into their constituent tones, imitated these tones with tuning-forks, and then, by recombining the sounds of the tuning-forks, he succeeded in reproducing the vowel sounds artificially.

Wood Wind.—The reeds and membranes we have been speaking of have each its own period of vibration, and the tone is determined by that period, which depends on the size and stiffness or tension of the reed. The varying tones of the voice are produced, as we have already pointed out, by alteration in the shape of the glottis and the tightness of the vocal cords. But in a wood wind instrument like the clarinet, one reed has to act for the whole series of notes. In such instruments the reed is very light and loose, and capable of vibrating in sympathy with the column of air it belongs to. The length of this column of air is altered by the position of the fingers on the stops, as in the flute.

Brass Instruments.—In brass instruments, such as the French horn, the place of the reed is taken by the lips of the performer, stretched across the mouthpiece. There is some difference of opinion as to whether the lips have their own period of vibration, like the vocal cords, or whether, like the light wooden reed

of the clarinet, they take their time from the resonating air column in the instrument. The opinion of performers seems in favour of the former explanation. This is confirmed by the fact that many notes can be sounded faintly by the lips using a mouthpiece alone; but the presence of the resounding column of air is necessary to make the vibrations *steady*, as well as to re-enforce the tone.

CHAPTER V

DISCORD AND HARMONY

Musical Flames—Interference—Beats—Discord and Harmony—Tempered Intonation.

Musical Flames.—It has been stated (p. 480) that, to make a column of air in a pipe vibrate, it is necessary to create a flutter near the end of the column. In a flute this is done by blowing sharply across the edge of the mouthpiece. A flame can be made to serve the same purpose. When we blow gently at a candle flame it flutters. The flutter is made up of pulsations of all sorts of frequency, any one of them capable of starting vibrations of the same frequency in a column of air. Take a straight piece of tin tubing of diameter 3 or 4 inches, and lower it gradually down over a lighted Bunsen burner. The air in the tube begins to vibrate, and as the tube is lowered the noise becomes almost deafening, and the pulsations become so violent as sometimes to extinguish the flame. Similar, but less violent, effects can be produced with glass tubes over small pinhole burners, with the additional advantage of the beautiful vibrations of the flame being visible. Take two glass tubes of different lengths and a paper slider tightly fitting over the shorter tube, so that it can be lengthened by pulling up the slider. Place the tubes over two pinhole burners, as shown in Fig. 21, and lower the shorter tube till it begins to sound its note. Then raise the paper slider. The note becomes gradually deeper; and when the tube becomes the same length as the other, sym-

pathetic vibrations are started in that, so that it too begins to sound its note.

Interference of Sound Waves—Beats.—Long tin tubes over Bunsen burners give very loud deep notes, and give a convenient way of illustrating what musicians call **beats.** For this two tubes 3 or 4 ft. in length should be taken, one of them being fitted with a slider by which its length can be increased. Hold these tubes over two lighted Bunsen burners (preferably large safety Bunsens), and they sound the same note if their length is the same. Now pull out the slider so as to increase the length of one tube by 2 or 3 in., and at once a throbbing in the sound becomes noticeable, the throbs following with greater rapidity as the slider is pulled further out. With tubes 4 ft. and 4 ft. 2 in. long there would be four throbs a second. When the slider is pulled out so far that the throbs cannot be counted, the sensation becomes painful to the ear, what we call a **discord.** These throbs, or **beats** as they are called, are due to interference of the two sets of sound waves. An explanation of the notion of interference is given in the chapter on Wave Motion (p. 445). Suppose we have two sets of sound waves, one set spreading out at the rate of 200 a second, and the other set at the rate of 201 per second. Suppose also that a wave of one set reaches our ear exactly at the same moment as a wave of the other set. A second later the same thing happens; but in the meantime the waves have not been arriving simultaneously; in fact, just half way between, a crest of the first set of waves has arrived simultaneously with a trough of the other set, and supposing the two sounds to be of equal intensity, the result at

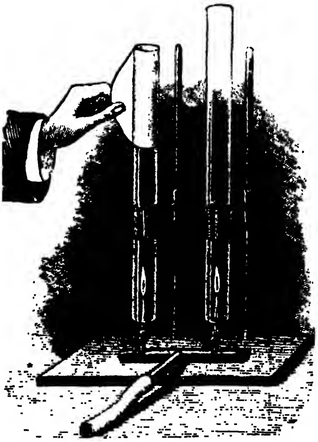


Fig. 21.—Singing flames.

that precise moment must have been *silence*. Once every second then the sound swells to a maximum, and once every second it falls to a minimum, and the effect on the ear is a heavy throbbing, one throb every second. If the two sounds have vibration numbers 200 and 205, the throbs are at the rate of 5 every second. For, since these numbers correspond to 40 and 41 waves in each fifth of a second, it is plain that there is one beat in each fifth of a second. The number of beats a second is always the difference of the vibration numbers of the two sounds to which the beats are due.

Discord and Harmony.—There is nothing very unpleasant in slow beats, and with low tones whose vibration numbers are small, discords are not very noticeable, and only a practised ear can tell whether a low note is out of tune. But when the beats amount to 30 or 40 per second, the roughness of the sound becomes most acute. When the number becomes greater than this the ear begins to lose its perception of the alternations in the sound, which becomes more and more continuous. It is found that the roughest discords are due to beats of from 30 to 40 per second. A difference of a semitone in the upper part of the scale would give a discord of this kind. But lower down the scale the difference in the frequencies is smaller. For instance strike simultaneously the lowest C and C sharp on the piano. You hear about 2 beats a second, and your ear is not offended. The frequencies are 33 and 35. But go up four octaves and strike the C and C sharp there. The frequencies are 528 and 561, and the discord is very acute.

It is now easy for us to understand why tones whose frequencies bear simple ratios to each other should give pleasing harmonies when sounded together. Take for instance the middle C of the piano and its fifth, the G above it. Their frequencies are 264 and 396, so that three vibrations of the former occupy the same time as two of the latter, and the two sets of waves will coincide in phase 132 times every second; in fact the tone of the C an octave below is distinctly audible when these two notes are sounded together. For further illustration the

chapter on Wave Motion (p. 430) should be consulted. The dark line in Fig. 22 shows the wave form resulting from a tone and its fifth.

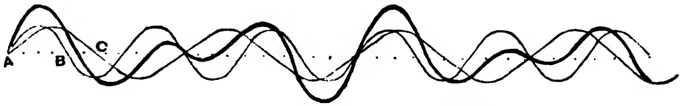


Fig. 22.—Resultant wave—tone and its fifth.

Tempered Intonation.—The intervals on the pianoforte, and other instruments with keyboards, are not absolutely true. This deviation from true intonation is not offensive, because our ears can be educated to accept, as true, intervals which are (within narrow limits) not true. The ratios of the frequencies of the octave are

$$\begin{array}{ccccccccccccccc} C & : & D & : & E & : & F & : & G & : & A & : & B & : & C' \\ 24 & : & 27 & : & 30 & : & 32 & : & 36 & : & 40 & : & 45 & : & 48 \end{array}$$

Notice that $C : D = 8 : 9$ and $D : E = 9 : 10$.

It is plain then that the interval $C : D$ (one in eight) is greater than the interval $D : E$ (one in nine). If a piano were tuned for the key of C, then it would not be in tune for the key of D, because E, which ought to be a full tone above D, would be a trifle flat. Accurate or just intonation would necessitate separate key boards for different keys, or at any rate a much larger number of notes than there are at present. The difficulty is got over by dividing the octave into twelve equal intervals, which are called semitones. Then C to D is two semitones, or a full tone, and six of these should take us up to C′, whose frequency is to that of C as 2 to 1. Suppose we take the ratio of frequencies for a full tone as $\frac{9}{8}$. Now

$$\left(\frac{9}{8}\right)^6 = \frac{531441}{262144} = 2 \times \frac{531441}{524288} = 2 \times \frac{74}{73} \text{ nearly.}$$

If this little deviation $\frac{74}{73}$ be distributed over the twelve semitones of the octave, no interval except the octave will be absolutely true: but one key will be as much in tune as another. This modification of the intervals is called **Equal Temperament** and is found more or less in the keyboards of pianos and organs.

CHAPTER VI

Instruments for the Reception of Sound

The Ear—The Phonograph—Sensitive and Manometric Flames.

The Ear.—The most remarkable property of the ear is its power of distinguishing the quality of sound. We know that the pitch of a sound depends on the rapidity of the vibrations, and the loudness on the amplitude (or length of swing) of these vibrations. Yet, in addition to the power of recognising pitch and loudness, the ear has the faculty of distinguishing between different musical instruments, of telling 'what is piped or harped.' Now the *quality* of sound depends on the proportion and strength of the upper partials which accompany the fundamental tone; and the *form* of the waves in the air must be altered by the presence of these upper partials (see Wave Motion, p. 431). But two waves of the same quality may yet have a different form. This is manifest from Fig. 23, taken from Helmholtz's great book, *Sensations of Tone.* A is the wave form of a fundamental tone, B that of its twelfth. In C and D the dotted lines are copies of A for purposes of comparison, while the other line is the curve compounded of A and B. In C the two curves are compounded as they stand; in D the curve B has been first slid half a wave's length to the right and then added to A. There is considerable difference between the two compound wave forms, and yet the ear would be incapable of distinguishing any difference in the qualities of the sounds which they represent. The ear would in fact separate the complex sound into the two components, and a trained listener could distinguish them. It would seem that the

ear has some apparatus for separating a compound motion of the air particles into its constituents, and transmitting them separately to the brain. It has been supposed that each minute fibre of the auditory nerve, the nerve that connects the labyrinth of the ear with the brain, has its own special tone to which it responds. To illustrate this point, a further experiment in sympathetic vibrations (see p. 478) should be made. Raise all the dampers of the notes of a piano by putting down the open pedal, and sing sharply the vowel sound *ah* against the sounding board, stopping to listen for the response. Each wire will select the particular constituent of the sound which is in sympathy with it, and the

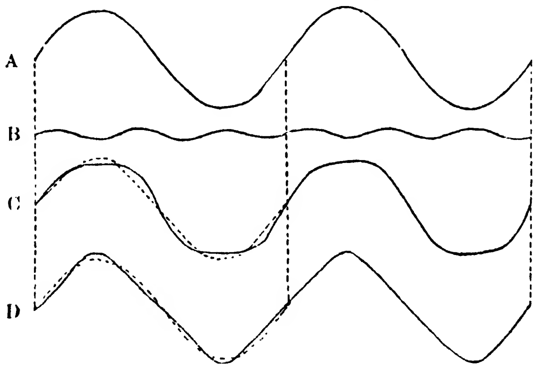


Fig. 23.—Compound wave forms.

compound tone given back by the wires will be a surprisingly perfect *ah*. 'Damp' the wires by taking the foot off the pedal, then press it down again, and try the same experiment with *oo*, then with *ee*. In each case the wires reproduce the sound. Now we may suppose the different fibres of the auditory nerve to act like the piano wires, and each to select that particular ripple in the big wave with which it is in sympathy. The mechanism by which the sound is communicated to these fibres is given, life size, in Fig. 24.

D is the funnel-shaped entrance to the outer passage called the **meatus**, which is narrowest in the middle. CC is the drum-skin separating the outer air from the inner cavity, the

tympanum or **drum**, BB. This is connected with the throat by a tube E called the **Eustachian tube**, which is usually closed, but opens in the act of swallowing. This is the only connection of the drum with the outside air; but the occasional opening of the tube ensures that the air in the drum is at the same pressure as the air outside. A series of three small bones connects the **drumskin** with the **labyrinth** A. This labyrinth is a

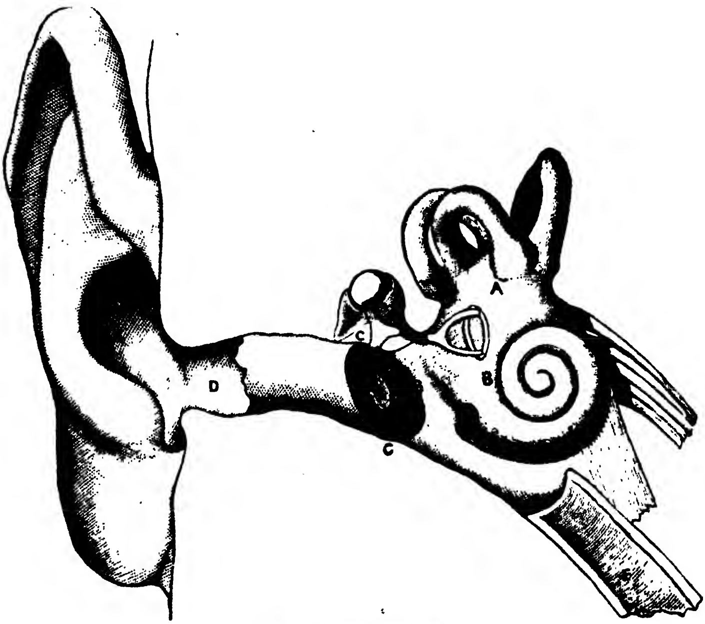


Fig. 24.—Mechanism of human ear.

chamber in the petrous bone of the head, filled with fluid, and of a curiously complex shape. Part of it is like a snail's shell, and is called the cochlea. With the labyrinth are connected the fibres of the nerve of hearing. The drumskin and the three small bones of the ear—the **hammer**, the **anvil**, and the **stirrup**, form a wonderful contrivance for converting the vibrations of the outside air, which are of small force but comparatively large amplitude, into vibrations of small amplitude but great force

communicated by the stirrup to the labyrinth. This chain of bones, shown faintly in Fig. 24, is given enlarged in Fig. 25.

The Phonograph.—Edison's phonograph is in its principle a simple instrument, though its details are worked out to perfection with wonderful ingenuity. It consists in the first place of a mouthpiece A (Fig. 26), with a drumskin B of extremely thin glass to which the vibrations of the air are communicated, and to which a graving point G is attached. If this point is in contact with a soft substance, a vibration communicated to the drumskin will make the needle pierce into the soft stuff, the stronger the vibration the deeper the hole. The soft substance is a 'wax'

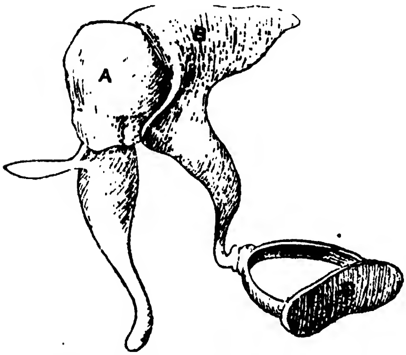


Fig. 25.—Hammer, anvil, and stirrup.

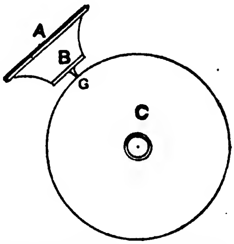


Fig. 26.—Section of phonograph.

cylinder C, which rotates uniformly, at the same time moving very slowly lengthwise, similarly to the arrangement in Fig. 3, so that when the drumskin is at rest the graving-point traces out on the cylinder a spiral groove of uniform depth. But when a sound sets the drumskin in vibration, the depth of this groove is not uniform but graven into hills and valleys corresponding to the rarefactions and compressions of the air. In this way a faithful record of the sound is made in 'wax.' To reproduce the sound, another more delicate point attached to a similar drumskin is made to work in the same groove. The cylinder is rotated and shifted sideways at the same pace as before, and thus the second membrane reproduces exactly the move-

ments of the first. These movements communicated to the air result in the same sounds as those which originally dug out the groove.

The refinements of detail extend only to the apparatus for giving motion to the cylinder of wax, the material of the 'wax,' and resonators or arrangements for making the sound audible.

Sensitive and Manometric Flames.—Sometimes when a gas jet is turned up too high, it roars. This roaring and fluttering of a flame, as described above (p. 490), is due to friction between the air and the heated stream of gas. If the flame is turned down, a point may be reached where it just ceases to roar, but where a very little disturbance in the air will set it off roaring. With an ordinary gas jet at ordinary pressure, it is difficult to get to this point; and some special arrangement is necessary to obtain a really satisfactory sensitive flame. Professor Tyndall's vowel-flame is made by a narrow stream of gas issuing at very high pressure from a pinhole steatite burner. In this way he obtained a flame about 2 ft. high, extraordinarily sensitive to sounds. A sharp sound like a hiss or the jingling of a bunch of keys makes this flame shrink down to a few inches, and the flame is even able to show the difference between the vowels. *Oo* has no effect on it, *o* makes it quiver, *ee* has a stronger effect, and *ah* a still stronger. This confirms what Helmholtz discovered about the vowels. The flame answers most to sharp sounds; and those vowels in which there are most of the higher upper partials have the greatest effect on it. For a description of this flame and others the reader is referred to Tyndall's *Sound.* We will, however, describe a remarkably sensitive flame discovered by Mr. Philip Barry, which can easily be constructed, and which has the great advantage of requiring no pressure of gas beyond that in the gas mains. A pinhole burner (a glass tube drawn out to a neck and filed off answers the purpose) is fixed about 2 inches below some fine wire-gauze, of about thirty-two meshes to the inch, laid on the ring of a retort stand (see Fig. 27). The gas is turned on and lighted above the gauze. If the gas is full on, the flame roars or flutters. If the gas be turned down gradually till the fluttering just ceases, a yellow cone of

flame is obtained which, at any sharp sound, such as the jingling of keys or the sounding of the letter *s*, shrinks down to the gauze. It is curious to see this flame jump at every *s* that occurs in ordinary conversation. A further development can be made by fixing a glass tube, a foot or more in length, over the flame. When the flame is turned up high the tube gives its note loudly; when low, no sound is heard; but when the gas is lowered to the sensitive point, a sharp sound or the whistling of the note of the tube makes the tube sing.

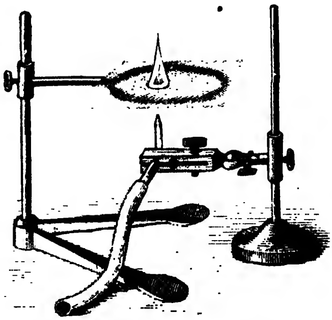


Fig. 27.—Barry's sensitive flame.

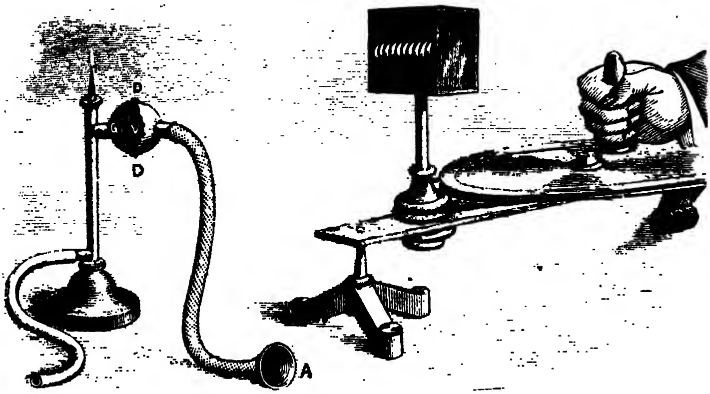


Fig. 28.—König's manometric flame.

In **König's Manometric Flame** the vibrations of the air do not affect the flame directly, but through a stretched diaphragm which is in contact with the unlighted gas. A spherical chamber (Fig. 28) is divided by a stretched rubber diaphragm DD into two parts, one of which V is open to the air, and the other G to gas which issues through a small pinhole burner. A speaking-tube

A is connected with the open compartment V of the chamber. The vibrations of the voice of course make DD vibrate, and so cause the flame to jump. But the eye is not quick enough to see any change in the flame. To see the change, it is necessary to look at the reflection of the flame in a rotating mirror (Fig. 28). When the flame is steady, the reflection appears as a long band of light, but when a note is sung into the mouthpiece, the vibrations of the flame are shown by this band being divided into separate forks of flame (Fig. 29), the up and down motion of the flame being shown by the forward inclination of the forks.

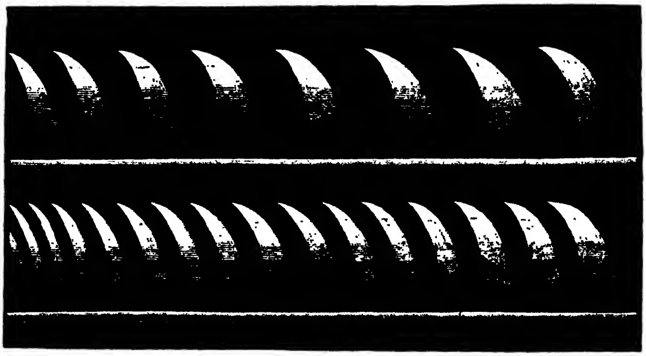


Fig. 29.—Manometric flame.

Fig. 29 gives representations of the appearance produced by different tones and combinations of tones. A simple tone produces a regular succession of deep indentations; when the tone is complex and rich in upper partials, these make themselves manifest by further small indentations, so that the quality of the sound can be accurately judged from the form taken by the reflection in the rotating mirror. The shape of the serrated bands will be found to correspond very closely with the shape of the grooves cut out by the same sounds in the wax cylinder of a phonograph.

LIGHT

CHAPTER I

Nature of Light

Luminous and Non-luminous Bodies Velocity of Light—Römer's observations of Jupiter's Satellites—Two Theories as to the Nature of Light—Definitions.

Nature of Light.—Light is that part of the mechanism of the universe which by its action on our eyes enables us to see things. It is plain that light must be something external to the eye, for in the absence of light the most powerful eyes can see nothing. When we see an object, light comes to our eyes from that object. Some bodies, such as the sun, or a candle, have light of their own. Such bodies we call **luminous,** or self-luminous. There are others which are **non-luminous.** The objects in a dark room are invisible to us until a match is struck; then they become visible to us, because some of the light from the match falls on them and from them travels to our eyes. The moon may be said to be non-luminous, because the light which she sheds on us comes originally from the sun; and the part of the moon on which the sun is not shining is invisible to us, or if visible owes its visibility to earth light.

Velocity of Light.—The discovery that light possesses a finite velocity made an epoch in the history of man's knowledge. For all distances on the earth the speed with which light travels is so great as to seem infinite. Until 1676 it was thought that

light was transmitted instantaneously; astronomy, then, proved the contrary.

The planet Jupiter has been closely watched by astronomers of all ages. Since the invention of the telescope his four chief moons have also been observed, and their motion round him accurately determined. The Danish astronomer, Römer, calculated the times of eclipse of one of the moons, *i.e.* the instants at which it should pass behind the planet and emerge from his shadow; and he noticed considerable discrepancy, sometimes amounting to fifteen minutes, between the calculated and the observed time. He noticed also that, when Jupiter and the earth were on the opposite sides of the sun, the moon was always later in its appearances and disappearances than it should be, according to the calculations made when Jupiter and the earth were on the same side of the sun; also that when the earth was once more on the same side of the sun as Jupiter the observed times agreed once more with the calculated times. He reasoned from this that the apparent unpunctuality was due to the greater distance through which the light had to travel. Thus in Fig. 1, if S be the sun and J Jupiter, something happening at J will be seen at E before being seen at E′, if light takes time to travel; and an observer who has calculated the instant of an eclipse of J's moon, on the supposition that his own distance from Jupiter is EJ, will find his calculated time too early if he be removed to the point E′. The diameter of the earth's orbit being known, it is easy to find the distance EE′. This distance divided by the difference between the observed and the calculated times will give the velocity of light. Römer determined it at 192,000 miles per second. This is too great, owing to his having used an incorrect value for the diameter of the earth's orbit. Recent determinations by direct methods, invented by the Frenchmen Foucault and Fizeau, fix the velocity of light at about 186,000

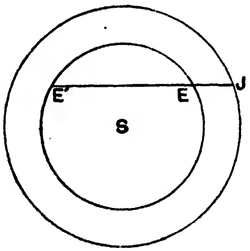


Fig. 1.
Eclipses of Jupiter's moons.

miles per second. Various other methods have been used to determine this; it is enough for the present to say they all agree fairly closely.

Two Theories of the Nature of Light.—Light then is something which travels with a known speed. Two great theories were started, and for a long time discussed, as to what it was that travelled. Is light a thing, or a state of things? In the chapter on Wave Motion (p. 422) we have given an illustration of each kind. A procession is passing along a crowded street. The crowd remain in their places, but a disturbance, an excitement, a cheering and waving of hats, moves along the crowd at the same pace as the carriages that form the procession. Is light something of the nature of the procession, that is to say, a stream of luminous particles, or is it a disturbance, a stream of waves passing through some crowd, some medium capable of being disturbed? The first theory, that light is a stream of luminous particles or corpuscles emitted by the luminous body, is called the *emission* theory or the *corpuscular* theory. It was supported by Sir Isaac Newton, who worked it out with the utmost ingenuity and skill; and his great name and reputation helped to make it generally accepted for a very long time. But it was found incapable of explaining many phenomena discovered since Newton's time, and it has now been abandoned. The other theory, that light is a disturbance travelling in some medium, is called the *undulatory* theory or *wave* theory. "The true founder of the wave theory is undoubtedly Huygens, who in 1678 first stated it in a definite form, and in 1690 published a satisfactory explanation of reflection and refraction on the supposition that light is due to wave motion in the ether."[1] For a long time Newton himself was favourably inclined to this theory, but finding it unable to account for the propagation of light in straight lines, and also polarisation, he finally discarded it. We have shown (WAVE MOTION, p. 450) how the passage of light in straight lines and the theory of shadows follow at once on the assumption that the wave-length of light is very small. Polarisation will be

[1] Preston, *Theory of Light.*

considered when we come to it, and all the phenomena of light will be referred to and explained by the wave theory. If we find this theory capable of explaining all the observed facts and of predicting facts since observed, we must feel as convinced of its truth as of that of the laws of gravitation; and we shall be prepared to accept the assumption that it demands, viz., that all space is filled with a mysterious medium, the ether, whose undulations, when they affect our sense of vision, we call light. For the present, it may simply be stated that the wave theory was laid on one side until Dr. Thomas Young, at the beginning of the nineteenth century, discovered the principle of interference, and by its means explained the rectilinear propagation of light. However, his work passed unnoticed for many years. "To the celebrated Frenchmen, Fresnel and Arago, Young was first indebted for the restitution of his rights; for they, especially Fresnel, independently remade and vastly extended his discoveries." [1]

Definitions of Terms Used—Transparency.—When light passes through a body without being scattered, the body is said to be transparent. Objects viewed through transparent bodies are distinctly visible. Glass, water, and certain crystals are transparent bodies. A perfectly transparent body is itself invisible. Glass when thin and perfectly clean sometimes approaches to this state.

Translucency.—When a body allows light to pass through it, but at the same time scatters some, so that objects are not distinctly visible through it, the body is said to be translucent. Ground glass is an instance of a translucent body.

Opacity.—When a body does not allow light to pass through it, it is said to be opaque. Metals are opaque substances. The division between the above classes is not very well marked. For instance a great depth of water is opaque, and a very thin sheet of gold is translucent.

A substance which transmits light is called an **optical medium**, or simply a **medium**.

Absorption.—When light falls on the surface of a body

[1] Tyndall's *Light*.

three things are possible. It may go on and pass through if the body is transparent or translucent, it may simply have its course changed at the surface of the body without entering the body at all, or it may enter the body and not pass out again, but be **absorbed**. It is not lost, even in this latter case, for it has an effect in heating the body.

CHAPTER II

Rectilinear Propagation of Light

Experiments—Inference—Notion of Rays—Pencils—Shadows.

Experiments.—A pinhole is made in a sheet of cardboard (Fig. 2) and the cardboard placed in front of a candle in an other-

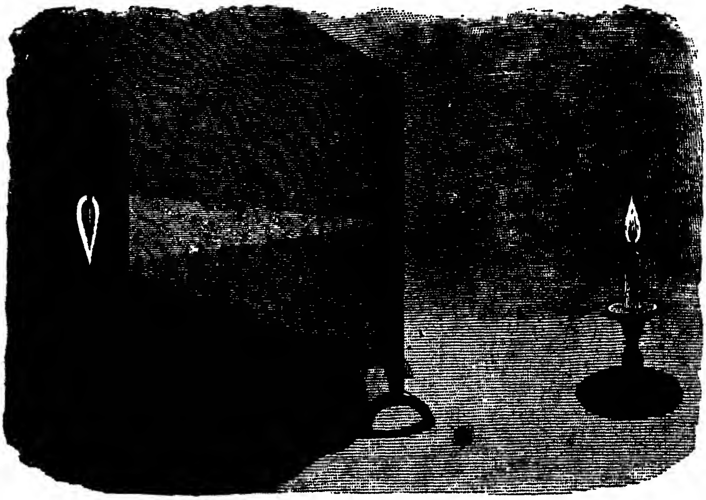


Fig. 2.—Pinhole image of candle flame.

wise darkened room. On the other side of the cardboard a screen of ground-glass or tissue-paper is placed so that the light from the candle can only reach the screen directly through the pinhole.

An inverted image of the candle flame will be thrown on the screen. Each portion of the candle flame AB sends light in a straight line through the pinhole P. The straight lines cross at the pinhole and the image A′B′ is therefore inverted. If we make two pinholes we shall get two images. Increase the number of pinholes and the number of images thrown on the screen will increase and will at length overlap until, when the pinholes have become one large hole, we shall have a uniform illumination, due to an infinite number of images of the candle flame overlapping one another.

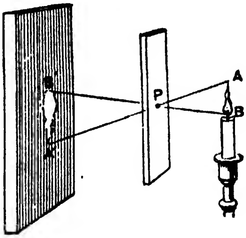


Fig. 3.—Diagram.

Fig. 4.—Image of sun through small hole.

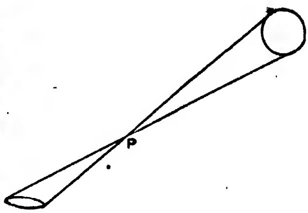


Fig. 5.—Diagram.

A similar experiment may be made by admitting sunlight direct through a small hole in a shutter into a darkened room (Fig. 4). On the floor will be thrown not an image of the hole

(which may be triangular, or of any shape) but an image of the sun. This is because the hole is so small, compared with the sun's disc, that it is practically a point P and forms the vertex of a cone whose base is the sun's disc (Fig. 5). This cone being produced is cut by the floor or a screen in an ellipse (or in a circle if the screen be put at right angles to the direction of the light). If the screen be brought up close to the hole, the image thrown will then be of the shape of the hole. The same thing may be noticed when sunlight passes through the leaves of trees. On the ground round or oval images of the sun are thrown.

'The motes which people the sunbeams' in a dusty room show the sunbeams to be straight lines; and the lines of sunlight breaking through clouds are familiar illustrations of the straight path followed by light.

Inference—Light travels in Straight Lines.—This statement will be modified later, for light possesses the power of

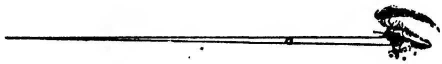


Fig. 6.—Pencil of rays filling the pupil.

bending round corners to a certain very small extent. This bending is called **diffraction** (see p. 588).

Notion of Rays.—The notion of rays is explained in WAVE MOTION (p. 450), and it is convenient to assume for many of our investigations that light travels in geometrical straight lines. A geometrical line, however, has no breadth, and a single ray, even if it could exist, could have no effect on our eyes. It must be remembered then that when we speak of a ray we mean a small bundle or **pencil** of rays formed by joining every point on a small portion of the wave surface to the centre from which that wave surface came (Fig. 6).

When the source of light is very distant, as a star, the wave surface is practically plane, and the rays in consequence are practically parallel (Fig. 7). The pencil is called a **parallel pencil.** When the wave surface is concave or converging on a single point the pencil of rays is said to be a **convergent pencil**

(Fig. 8). When the surface is convex, the pencil of rays is called a **divergent pencil** (Fig. 9).

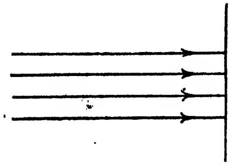


Fig. 7.—Parallel pencil.

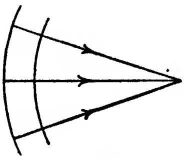


Fig. 8.—Convergent pencil.

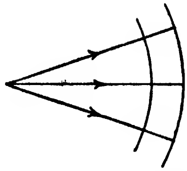


Fig. 9.—Divergent pencil.

Shadows—Experiments.—Take a source of light as small as possible, such as a pinhole in a cardboard screen placed close to a lamp (Fig. 10). The shadows thrown upon a white screen by any opaque object, such as a pencil, placed in the stream of light,

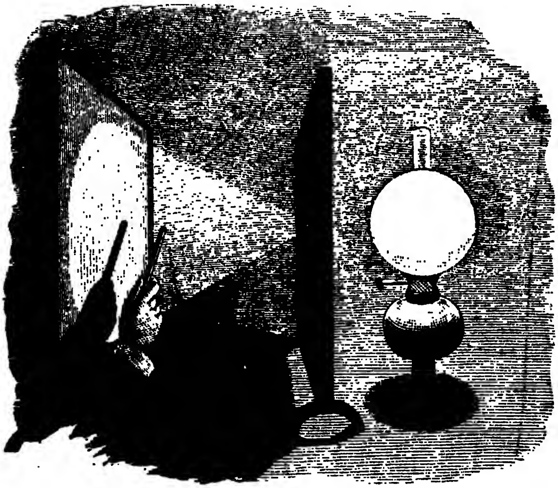


Fig. 10.—Sharp shadow.

are sharp and distinct. If the size of the pinhole be increased, or if the cardboard screen be taken away from the lamp, the edge of the shadow becomes indistinct, unless the pencil be held quite close to the paper. The same thing may be noticed with

sunlight. If a hair is held in the sunlight close to a piece of white paper it throws a distinct black shadow: but the farther it is taken away from the paper, the fainter and more indistinct in outline does the shadow become, until it disappears altogether. Notice also the shadows cast by buildings and trees, how as the sun declines and the shadows lengthen their edges become indistinct.

Shadows—Explanation.—When the source of light is a point, all rays diverge from this point and the shadows cast will be perfectly sharp and distinct. In hardly any cases, however,

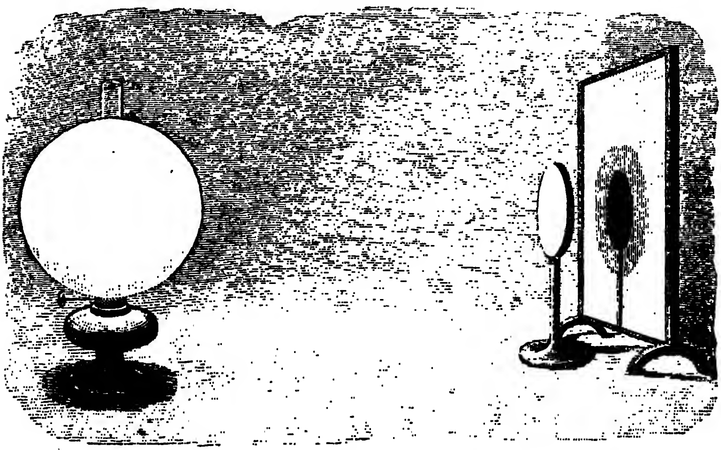


Fig. 11.—Shadow and penumbra.

can our source of light be considered as a luminous point. In general it is a patch of light, every point in which throws its own shadow. In consequence the boundary of shadows is generally indistinct. The shadows thrown by the sun, for instance, are never sharp except when the surface on which the shadow is thrown is quite close to the object which throws the shadow. The diagram (Fig. 12) serves to explain the facts depicted in the engraving (Fig. 11). C is an evenly luminous globe, and AB is a section of an opaque disc which throws a shadow on the screen XY. Drawing the outside tangents from A and B (and

all other points on the circumference of the disc) to the globe, it is plain that there will be a circular patch, diameter DE, on the screen, on which no light at all falls. Drawing the inside tangents, we get another circular patch, diameter FG, outside of which all points of the screen receive the full benefit of the globe's light. But between these two circles is a ring which is neither entirely in the dark nor entirely in the light. The point P in our figure receives light from all points of the globe above PQ, or rather all points that are outside of the cone whose vertex is P and base the disc AB. The disc DE we may call the full shadow or **umbra**, while the region between the two circles, whose diameters are DE and FG, is called the **penumbra**.

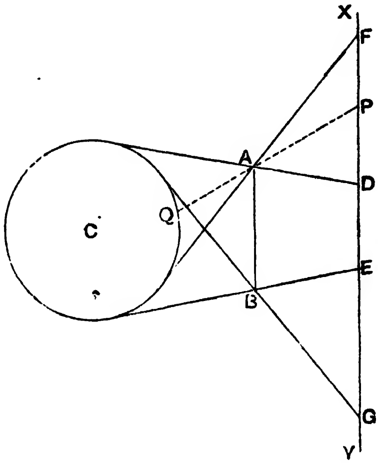


Fig. 12.—Diagram.

The penumbra of the earth's shadow is a very marked feature in eclipses of the moon.

CHAPTER III

Intensity of Illumination

Experiments—Explanation—Law of Inverse Squares—Photometers.

Experiments. — Take a lamp and cardboard screen with a pinhole, as in Fig. 10, and in the stream of light put another cardboard, screen with a square hole cut in it. On the white screen beyond a square patch of light is thrown, which increases in area and diminishes in brightness as this white screen is removed to a greater distance. The decrease in brightness is rapid. This fact can be shown in another way. In a room lighted by a single candle, find the distance from the light at

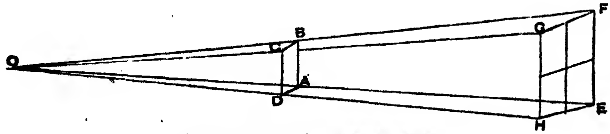


Fig. 13.—Law of inverse squares.

which a book of small print is just legible. Then light a second candle and place it beside the first. Although the light is doubled, the distance from it at which the book can be read is not doubled, because the intensity of the light decreases too rapidly. If four candles be lighted, the greatest distance of legibility becomes double of what it was with one candle only.

Intensity of Illumination—Explanation.—Let O be a luminous point, and ABCD a square aperture in a screen. Join O to

every point on the boundary of this aperture and produce. We have now a pyramid of light, and every point beyond the screen that is inside the pyramid will receive light from O, while points outside the pyramid will be in shadow. If another screen is put up parallel to the first, there will be thrown on it a square patch of light EFGH, which will increase in area as the second screen is moved farther off. As it is moved farther off the brightness of the patch will decrease rapidly. If the distance from A is doubled the area of the patch will be multiplied by four, and as a natural consequence the brightness will be a quarter of what it was. Theoretically this is what we should expect, no matter whether we adopt the emission theory or the wave theory. The argument from energy given in WAVE MOTION (p. 445) is equally applicable to a stream of luminous particles supposed to be diverging from a point. The practical proof depends on the method we adopt for measuring the intensity of the light. By theory we have this law—**The intensity of illumination at any point varies inversely as the square of the distance of that point from the source of light.**

Photometers.—An apparatus for measuring the brightness or intensity of light is called a photometer. All photometers depend on the law of inverse squares, but may also be used for confirming that law. **Rumford's Photometer** consists of a screen of ground-glass or unglazed white paper, in front of which stands an upright opaque rod C (Fig. 15). If two different sources of light A and B be placed on the side of the rod away from the screen, each will throw a shadow of the rod on the screen XY, though the shadow *a* receives light from B and the shadow *b* receives light from A. If the two lights be of equal intensity, the shadows will appear equally dark; but if one light be stronger than the other, the corresponding shadow will be darker, as it will only receive light from the weaker of the two.

In the figure (Fig. 14) the illumination of the lamp is to be compared with that of the candle. The lamp or the candle is shifted until the two shadows on the screen appear equally

dark, and the distances of the lamp and candle from the shadow which each illuminates are then measured. Let them be R

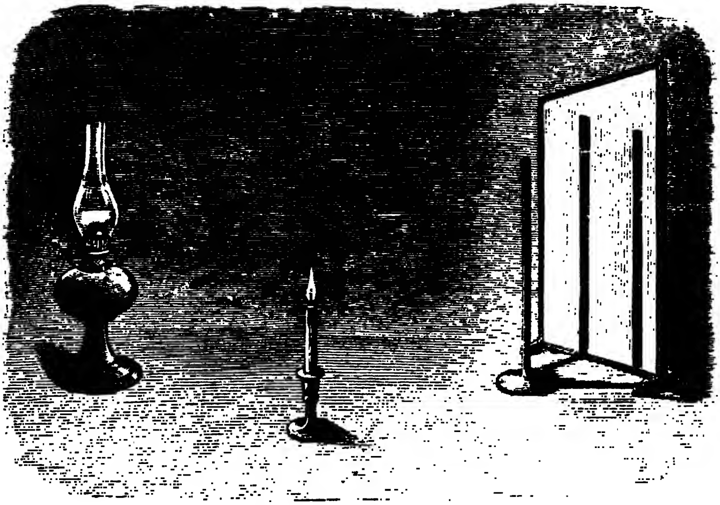


Fig. 14.—Rumford's photometer.

and r respectively. Then we have by theory—

$$\frac{\text{Intensity of lamp's light}}{\text{Intensity of candle's light}} = \frac{(\text{distance of lamp})^2}{(\text{distance of candle})^2} = \frac{R^2}{r^2}.$$

To use the apparatus to verify the law of inverse squares use as the two sources of light a single candle and a group of four of the same kind. When the group of four is placed at a distance from the screen double that of the single candle the two shadows will be of equal darkness.

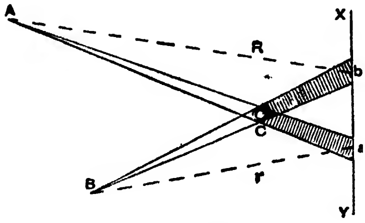


Fig. 15.—Diagram.

The unit by which intensity of light is measured is the intensity of the light of a **standard candle**, which is a wax candle of weight one-sixth

of a pound, burning at the rate of 120 grains an hour. When a source of light is equivalent to 20 of such standard candles, it is said to be of 20 candle-power.

Bunsen's Photometer.—When a piece of paper with a grease spot on it is held up against the light, the grease spot, being more translucent than the rest of the paper, appears brighter. On the other hand, when it is held so that the observer's eye and the light are on the same side of it, the grease spot will appear darker than the rest because it lets more light pass

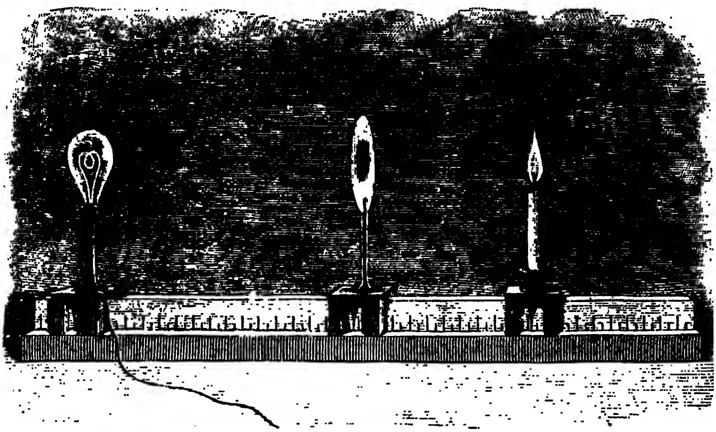


Fig. 16.—Bunsen's photometer.

through than the rest and reflects less. If now the two sources of light to be compared (B and C, Fig. 16) are placed one on each side of such a grease spot on the screen A, and shifted until the grease spot appears neither lighter nor darker than the rest of the paper, it follows that they are throwing lights of equal intensity on the paper. Then if I and I′ are the intensities of the two sources of light, and r and r' their distances from the paper, we have by the law of inverse squares—

$$\frac{I}{r^2} = \frac{I'}{r'^2}.$$

CHAPTER IV

Reflection of Light

Scattering of Light—Reflection at Plane Polished Surface—Laws of Reflection—Explanation—Reflection of Pencil of Rays—Images Inverted—Reflection of Light in two Mirrors—Kaleidoscope—Reflection always Incomplete—Irregular Reflection—Principle of the Sextant.

Scattering of Light.—When light falls on ground-glass, the surface of the glass presents a great number of *facets* which turn the light in all directions. Some passing through reaches the eye from every portion of the surface of the glass, so that the glass itself becomes visible at all points, and the original source of the light cannot be distinguished. The glass is then translucent, not transparent, and the light has been *scattered* at its surface. Some of the light merely has its direction changed

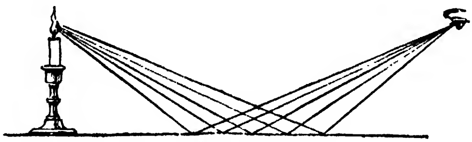


Fig. 17.—Scattering of light.

without passing through. It is irregularly *reflected* and scattered. In general, when light falls on an *opaque* body, some is absorbed and some reflected. Unless the surface of the body is polished, the light is reflected irregularly, and comes to the eye from all points of the surface of the body, so that all points of that surface are visible, as in Fig. 17.

When the surface is polished, however, a ray of light striking

it is reflected in one particular direction, and the eye no longer receives light from all points of the surface. The surface may in fact become invisible, as most of us have found by walking into a looking-glass on a staircase or in a shop. It is with polished surfaces that we have to do in investigating the laws of reflection of light, for polishing means the removal of irregularities in the surface.

Reflection of Light.—The instrument shown in Fig. 18 consists of a small plane mirror A placed at the centre of a semicircular tray; its surface passing through the diameter of the semicircle at right angles to the tray itself. In the rim of the tray small holes are bored at intervals of 10 degrees. A light held at one of the holes, say that marked 50°, is seen reflected at the mirror A by an eye looking through the hole

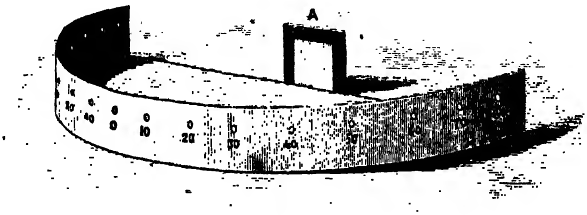


Fig. 18.—Reflection of light.

marked 50° on the other side. The hole marked 0°, which is immediately opposite the mirror, receives its own reflection.

Again, observe the reflection of objects in still water; notice that the 'reflection' or rather the image of each object is directly underneath the object itself.

Fig. 19 shows a telescope AB which can work on a vertical graduated circle. M is a bath of mercury. The telescope is pointed at a star S, whose altitude above the horizon is noted by reading the graduated circle. The telescope is then pointed in the direction A′B′ of the image of the star S′ in the bath of mercury M, and the graduated circle is read again. The difference of the two readings is double of the altitude of the star.

Hence S′ is found to be the same angular distance below the horizon that S was above it. The star is at such a great distance away that its rays falling on the surface of the mercury may be regarded as parallel to those falling direct on the

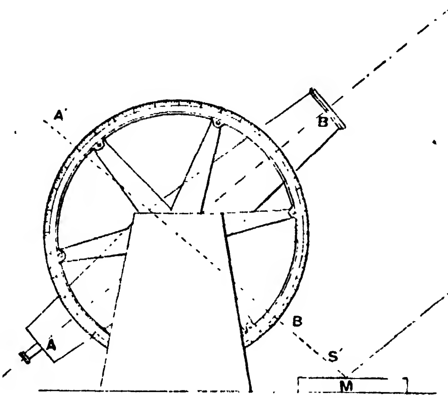


Fig. 19.—Mural circle.

telescope. The surface of the mercury is of course horizontal. So we find that the light after reflection makes the same angle with the surface as before reflection.

DEFINITION.—A straight line drawn from any point of a

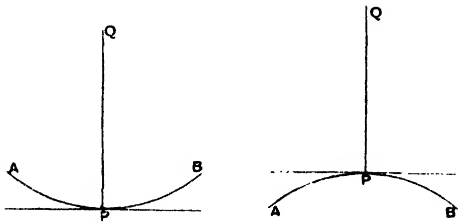


Fig. 20.—Normal to a surface.

surface perpendicular to the surface at that point is called a *normal* to the surface. In the case of a curved surface, as AB (Fig. 20), the direction of the surface at any point P is the direction of the tangent plane at that point, and the normal at

P is the perpendicular to the tangent plane at P, viz. the line PQ.

Laws of Reflection of Light.—(1) When a ray of light is reflected at a surface, the incident ray, the normal to the surface, and the reflected ray lie in the same plane.

(2) The angle between the reflected ray and the normal is equal to the angle between the incident ray and the normal, *i.e.* **the angle of reflection is equal to the angle of incidence.**

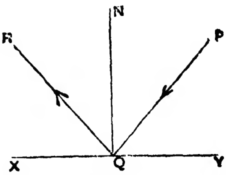


Fig. 21.—Laws of reflection.

Thus in Fig. 21, XY is a section of the surface which is supposed to be perpendicular to the plane of the paper. Hence the normal to the surface at Q will lie in the plane of the paper. A ray from P, a point in the plane of the paper, strikes the surface at Q, so that the incident ray PQ and the normal QN both lie in the plane of the paper. Then by law (1) the reflected ray QR will also lie in the plane of the paper, and by law (2) the angle RQN is equal to the angle PQN, and of course RQX is therefore equal to PQY.

Theoretical Explanation.—For an explanation of the laws of reflection according to the wave theory of light, see WAVE MOTION, pp. 441-443. Newton, working out his corpuscular theory, assumed his luminous particles to be perfectly elastic, in which case they would obey the laws of reflection.

Reflection of a Pencil of Rays in a Plane Mirror.—Let XY be a plane mirror, A a luminous point from which a pencil of rays AQ_1, AQ_2 etc. diverges. Let the reflected rays be Q_1R_1, Q_2R_2, etc. Now draw AM perpendicular to XY, and suppose it produced so that $MA_1 = MA$. Join A_1Q_1, A_1Q_2, etc. By Euc. I. 4 we have the angle $A_1Q_1M = AQ_1M$. But $AQ_1M = R_1Q_1Y$ by the law of reflection. Therefore $A_1Q_1M = R_1Q_1Y$, and therefore A_1Q_1 is in the same straight line with Q_1R_1. Similarly $A_1Q_2R_2$, $A_1Q_3R_3$, $A_1Q_4R_4$ are straight lines. Hence it is plain that all the rays after reflection appear to come from the point A_1. Therefore an eye suitably placed will see a *reflection*, or rather

an **image** of the point A in the mirror at A_1. Notice that the image is a **virtual** image, that is to say, the reflected rays do not actually pass through A_1, only their directions *produced* backwards pass through A_1.

[See also WAVE MOTION, p. 451.]

Images in a Single Plane Mirror.—Verify this by standing a mirror (a glass letter-weight does very well) on a flat sheet of paper, and sticking a pin into the paper upright; then by making two other pins stand in the same straight line with the image of the first pin, the course of the reflected rays may be drawn on the paper and proved to be as in Fig. 22.

If instead of a luminous point we now take a visible object

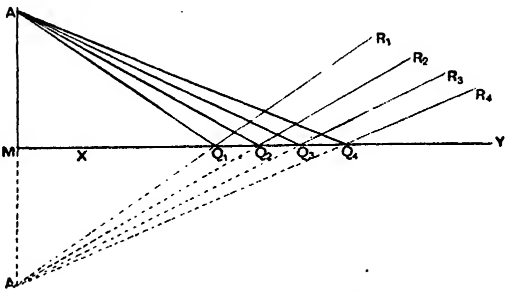


Fig. 22. Reflection of a pencil of rays.

of finite size, every point on its surface will behave exactly as the single luminous point in the preceding article. That is to say, light coming from any point of the object and reflected in the plane mirror will appear to come from a point so situated that the line joining it to the actual point is bisected at right angles by the plane of the mirror.

Thus in Fig. 23 A_1B_1 will be the image of AB in the plane mirror XY. Notice that the image is reversed. This of course is familiar to any one who has looked at himself in the glass. His right hand appears to be his left, and *vice versâ*, and if he parts his hair on the left side of his head his image will have its hair parted on the right. Writing or printing held in front of a mirror becomes reversed in the reflection. Write some words

on a sheet of paper and blot at once with clean blotting paper. The impression on the blotting paper may be illegible, but when held before the mirror becomes legible in the reflection.

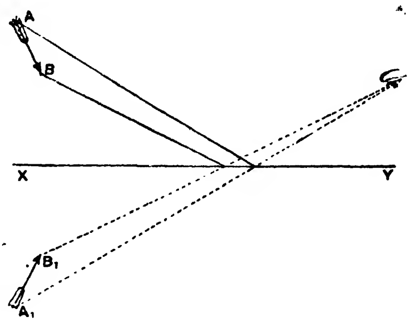


Fig. 23.—Reversal of image.

Reflection of Light in two or more Mirrors.—By making use of more than one plane mirror, it is possible to multiply images, the two laws of reflection being strictly followed in every case.

We will take two mirrors, making an angle of 60°, as presenting a case of special interest.

Let OA, OB (Fig. 24) be the two mirrors, each perpendicular to the plane of the paper. Let P be a luminous point. With centre O and radius OP a circle is described. The first image of P in the mirror OA is got as usual by drawing a perpendicular from P on OA and producing it to an equal distance on the other side. This will give us the point P_1 which lies on the circle. Now light appearing to come from P_1 may strike the second mirror and be again reflected, and so appear to come from the point P_2, obtained by drawing a perpendicular from P_1 on OB, and continuing it to an equal distance on the other side. A third reflection would give us an image P_3. Now take a ray reflected first at the mirror OB. Its first reflection will make it appear to come from Q_1, its second reflection will make it appear to come from

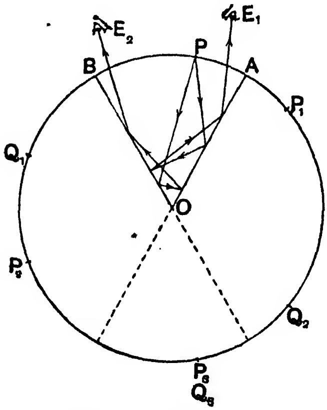


Fig. 24.—Kaleidoscope.

Q_2. If the angle between the mirrors is 60°, it is easy to satisfy ourselves that the third reflection will make it appear to come from Q_3, this image coinciding with the third image P_3 previously obtained. This forms the principle of the **kaleidoscope,** which consists of a tube with two long thin mirrors fitted inside it and inclined at an angle of 60°. An eye looking through the tube at an object at the other end will see not only the object but five images of it arranged in a pattern. Now if the object be shifted the images will also shift, and an endless variety of symmetrical patterns can be obtained.

In Fig. 24 we have drawn the course of two rays for three successive reflections. The eye E_1 is placed so as to see the image P_3, while the eye E_2 sees the image Q_3. In each case the path should be traced backwards from the eye to P. If the mirrors are not at an angle of 60°, P_3 and Q_3 do not coincide. The number of images is limited, because as soon as an image falls between the *backs* of the two mirrors, *e.g.* between X and Y, no further reflections can happen to the ray. It has to pass out into space.

Reflection of Light always Incomplete.—When we take two parallel mirrors, the number of possible reflections is infinite and the number of images of an object placed between them is also theoretically infinite. This must be familiar to those who have been in a room which has two large mirrors facing each other on opposite walls. The apparently endless suite of apartments that can be seen is very striking. But in practice the number of visible images is limited to twenty or so. The reason of this is that the whole of the light incident on a mirror is not reflected. Some of it is always absorbed. The quantity of light absorbed varies with the substance and also with the angle of incidence of the light. The best reflectors are polished metals, more especially white metals as mercury and silver. Ordinary looking-glass is silvered or coated with mercury at the back, and the reflection takes place at the metal surface behind the glass, though a small quantity of light is reflected at the outer surface. Black bodies absorb most light, white bodies least. It should also be noticed that the amount of light reflected increases with

the obliquity of the incident ray. For instance, a sheet of ordinary white paper will give an image of a candle flame if held so that the light may fall very obliquely on it.

Irregular Reflection.—The laws of reflection are of universal application, and all bodies that are not self-luminous are visible to us only by reflected light. But bodies which are not highly polished present such an infinity of small facets or reflecting surfaces to the light, that light travels to the eye from all parts of the surface (see p. 518). Snow is a striking example of the effect of a number of reflecting surfaces. A single crystal of snow is merely an ice-crystal, transparent but minute. In a quantity of such crystals light is reflected at innumerable facets and very little of it is absorbed, owing to the transparency of the substance. We have in fact 78 per cent of the incident light reflected and scattered from newly-fallen snow; this fact accounts for its whiteness. The whitest paper reflects 70 per cent of the incident light.

Deviation Produced by Rotation of Mirror.—Receive a ray of bright sunlight on a piece of bright metal and observe the motions of the spot of reflected light on a neighbouring wall (this experiment is sometimes known as 'flashing'). The angle travelled by the reflected ray is double of the angle through which the mirror is turned.

The angle between the incident and reflected rays being double of the angle between the incident ray and the normal, it follows that if the mirror be rotated through a certain angle, then the reflected ray must be rotated through an angle twice as large. This is shown in Fig. 25, PQ being the incident ray, and the dotted lines giving the position of the mirror, the normal, and the reflected ray after rotation through a small angle, then

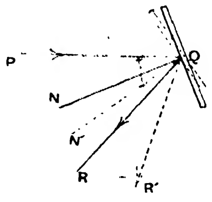


Fig. 25.—Rotation of mirror.

$$RQR' = 2NQN'.$$

The Sextant is used by seamen to ascertain the angular

distance between distant objects, and chiefly the angular distance of heavenly bodies from the horizon. To effect this the horizon is viewed directly through the telescope O (Fig. 26) in the direction OH, while the image of the object, *e.g.* a star, after reflection in the mirrors M and H, is made to coincide with it, that is the star appears to be in the same direction OH as the horizon seen direct. The angle SOH is the angular distance of the star from the horizon, which is to be measured by the sextant.

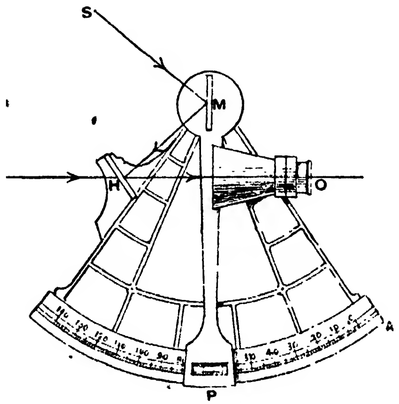


Fig. 26.—The sextant.

The 'index bar' MP, carrying the 'index glass' or mirror M is movable about M, and when the 'index' P is at A the index glass is parallel to the 'horizon glass' H; then an object seen direct through the telescope O coincides with the image of the same object seen after reflection at M and H, and a ray of light HM falling on the mirror M is reflected parallel to OH.

As the index bar is moved through the angle AMP, the angle SOH swept out by the reflected ray MS is twice the angle through which the mirror is turned (*see* Fig. 25). Hence the angle SOH (between an object seen in the direction OH and one seen also in the direction OH, but after reflection at M and H) is twice the angle AMP.

To simplify reading, each degree of the graduation on the arc AP is half of a degree of the angle AMP, hence the reading of the graduation at P is the correct value of the angle SOH. This is the angle at the eye subtended by the two objects, and in the case supposed is the altitude of the star.

CHAPTER V

Refraction

Refraction — Law of Sines — Refractive Index — Explanation in accordance with Theory — Refraction in Air — Astronomical Refraction—Critical Angle—Total Reflection — Mirage — Refraction at Parallel Surfaces—Succession of Images in thick Looking-glass—Total Reflection Prism.

Refraction (*Latin*, breaking).—Fig. 27 shows a glass trough with

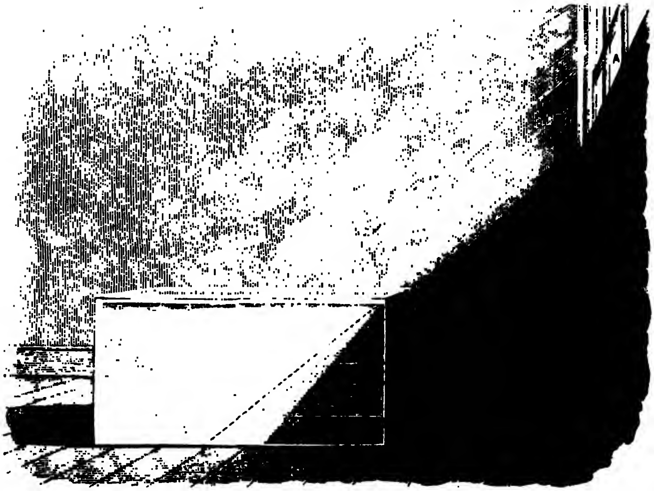


Fig. 27.—Refraction.

the side BC blackened or pasted over with paper. Sunlight coming from A throws a shadow of BC on the bottom of the

trough. The edge of this shadow is at E. Now fill the trough up with water and the edge of the shadow retreats to F. If the water be slightly tinged with milk, the course of the refracted light, which just grazes the edge of the trough, can be seen. It is a straight line, BF, but not in the same straight line with its former course AB.

Put a coin at the bottom of a teacup. Place the eye so that the coin is just hidden by the side of the teacup. Now pour water into the teacup and the coin becomes visible. In Fig. 28 the point P is seen at P′. Therefore the light emerging from the water at Q is bent into the direction QE.

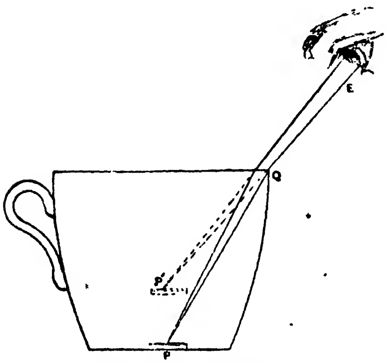


Fig. 28—Coin in a teacup.

Compare with this the well-known fact that a clean pool of water always appears shallower than it really is. The light from the pebbles at the bottom is refracted in just the same way as the light from the coin in the teacup. The apparent depth is $\frac{3}{4}$ of the real depth.

The same thing occurs when a straight stick or oar is partly in and partly out of the water. It appears to be bent at the surface of the water, each part of the stick below the surface appearing higher than it really is. Now the refracted portion of the stick appears straight, though not in the same straight line with the other portion; for all parts of the stick under the water are refracted upwards through distances equal to a quarter of their depths below the surface. For objects seen very obliquely, the upward shifting is greater than a quarter.

The glass trough in Fig. 27 can be used to prove that the course of light is the same if its direction be reversed. For a bright object placed at F when the trough is full of water is just visible to an eye placed in the line BA. This shows that

the light passing from water into air is bent away from the normal to the surface.

Laws of Refraction.—When light passes from one medium to another, its course is in general altered. A ray passing from air into water, for instance, is **bent** or **refracted**. The phenomenon of refraction has two fixed laws like that of reflection. The first law is the same as the first law of reflection.

(1) The incident ray, the normal to the surface at the point of incidence, and the refracted ray are all in the same plane.

(2) The sine of the angle of incidence bears to the sine of the angle of refraction a ratio which is constant for the same two media, and depends only on the nature of those media, and of the light (see page 542). This is called the **law of sines.**

In Fig. 29, XY is a section of the surface bounding the two media. NQN′ is the normal to the surface at the point of incidence of the light. The incident ray PQ is bent or refracted in the direction QR, the lines PQ, QR, NN′ being all in the same plane. Also if the angle PQN is called ϕ, and the angle RQN′, ϕ', we have $\frac{\sin\phi}{\sin\phi'}$ = a constant, which is independent of the angle ϕ, and depends only on the nature of the two media. The law may be stated without reference to trigonometry thus. Take equal lengths QA, QB along the incident and refracted rays. This has been done in our figure by describing a circle, centre Q. Draw perpendiculars AM, BM′ on the normal. Then $\frac{AM}{BM'}$ = this constant ratio.

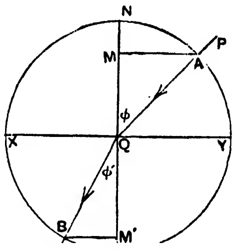


Fig. 29.—Snell's law.

The laws of refraction were discovered by a Dutch professor, Snell, in 1621. There is an important point to be noticed as to the direction in which the ray is deflected. In passing from a rarer medium into a denser medium, the ray is always bent towards the normal to the surface, and *vice versâ.* This can be expressed thus. The ratio $\frac{\sin\phi}{\sin\phi'}$ is always greater than 1 in pass-

ing from a rarer to a denser medium, and less than 1 in passing from a denser to a rarer medium. If we take air as our first medium, then in passing from air into water or glass or crystal, the ratio is always greater than 1 and depends on the nature of the second substance. Thus from air into water the ratio is $\frac{4}{3}$. This ratio is called the *refractive index* of the water. The following table gives roughly the refractive indices of a few substances. It will subsequently be seen that the refractive index differs for light of different colours. The numbers given in the table are for yellow light.

Air into	diamond	2·4
,,	flint-glass	1·65
,,	crown-glass	1·52
,,	alcohol	1·37
,,	carbon disulphide	1·65
,,	sea water	1·34
,,	pure water	1·33

Since the course of the light is the same if its direction be reversed, it follows that the refractive index from water into air is $\frac{3}{4}$ instead of $\frac{4}{3}$; and that in general, if μ_{AB} represent the refractive index from a substance A into another substance B, we have $\mu_{AB} = \dfrac{1}{\mu_{BA}}$.

Theory of Refraction.—Newton deduced the laws of refraction from his corpuscular theory of light by assuming that his luminiferous particles travelled faster in a denser medium. Then the refractive index would be in the inverse ratio of the two velocities. Assuming the refractive index from air into water to be $\frac{4}{3}$, then Newton said, 'the velocity of light in air is to the velocity of light in water as 3 to 4.'

The wave theory reverses this. It also explains the phenomenon of refraction as depending on the different velocities in the two media; but it requires that the velocity should be less in the denser medium; the refractive index is then the direct ratio of the two velocities. This appears the more reasonable assumption, and if it were shown that the velocity of light in water is less than that in air, the corpuscular theory

would be directly disproved. M. Foucault in 1850 by direct measurement showed beyond doubt that **the velocity of light in water is less than in air**, and this fact may be regarded as confirming the wave theory. For the explanation of the law of refraction according to this theory, see WAVE MOTION, p. 442, remembering that the angle between the wave surface and the refracting surface is the same as that between the *ray* and the normal. Fig. 23 in WAVE MOTION should be studied with reference to the appearances described at the beginning of this chapter.

Refraction in Air.—Under ordinary conditions and for short distances light travels in straight lines in the air. We are now in a position to consider exceptions to this rule. On a sunny day, when the surface of the ground is hot and the air cold, as is often the case in spring, the air near the ground becomes visible, and appears to be in a state of vibration. 'Shimmering' is the word used to describe the appearance. This is due to the air near the ground becoming heated and rising, and colder air taking its place, so that the density of the air at any point is continually changing, and with the density the refractive index also changes. Hence light from a distant object coming through regions of differing density has its course slightly changed every instant, and a vibration seems to be happening at those regions where the upward currents of hot air are strongest and most variable. The same appearance may be noticed above a gas-jet or chandelier, and when two liquids of different refractive index are mixed, *e.g.* whisky and water.

The density of the air diminishes as its height above the earth increases, and the refractive index decreases with the density. The atmosphere extends to a height of 200 miles or more, becoming rarer and rarer, and beyond the atmosphere, we suppose that there is nothing but the ether, the medium that transmits light,—no particles of ordinary matter to diminish the velocity of light. We should expect that light coming to us from a heavenly body would be retarded on entering our atmosphere, and therefore when entering it obliquely would

be refracted. The more oblique the incidence of the light, the greater the refraction, hence the light from a star near the horizon will be more refracted than if that star were higher in the heavens. This is a fact well known to astronomers, and in one form, the distortion of the sun's disc at sunrise or sunset, familiar to everybody.

In explaining what happens, divide the atmosphere into layers of gradually diminishing density. Remembering that the ray is always bent towards the normal to the surface on entering a denser medium, it will be evident that the course of light from a star S near the horizon H to an observer P on the earth's surface will be in the line *Sabc*P (Fig. 30), and there-

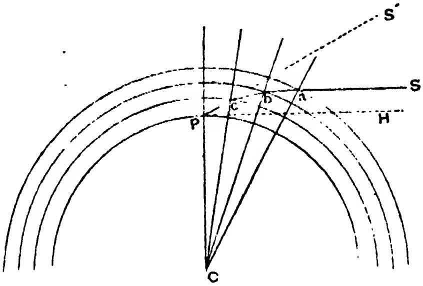


Fig. 30.—Astronomical refraction.

fore will appear to come in the direction *S'*P. The figure of course is much exaggerated. The normal to the surface at any point is the radius from C, the earth's centre, to that point.

The refraction is only slight until the source of light becomes very near to the horizon. Then the refraction increases rapidly and, in the case of the sun, the upper part of his disc is less refracted than the lower, and his vertical diameter appears shortened; this gives the sun an elliptical shape.

It may be remarked also that the apparent position of the refracted object is always higher than the real one. Owing to this the sun is frequently visible when he is actually below the horizon.

Critical Angle.—In passing from a denser to a rarer medium,

the ray is refracted away from the normal to the surface; *e.g.* from P in water to R in air (Fig. 31). Here $\frac{\sin PQN'}{\sin RQN} = \frac{1}{\mu} = \frac{3}{4}$, where μ is the *refractive index* of water (see page 530). Of the

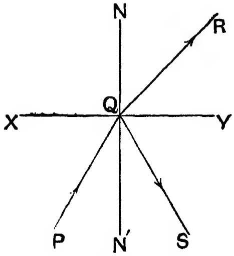


Fig. 31.—Light passing from water into air.

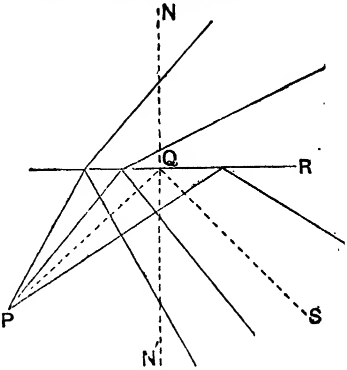


Fig. 32.—Critical angle.

light that strikes the surface in the direction PQ, not all emerges in the direction QR, some is internally reflected in the direction QS. When the angle of incidence is further increased (Fig. 32), the refracted light is nearer to the surface and more light is reflected, until a critical position is reached, which is indicated by the dotted line. Here QR coincides with the surface, and in that case RQN is 90°, sin RQN $= 1$, and sin PQN′ $= \frac{1}{\mu}$. What happens in the case where the angle PQN′ has a sine equal to or greater than $\frac{1}{\mu}$? The ray, being unable to emerge, is totally reflected at the inner surface of the denser medium. The angle PQN′ at which this phenomenon begins is called the **critical angle.** Light cannot pass from a denser medium into air when the angle of incidence is greater than

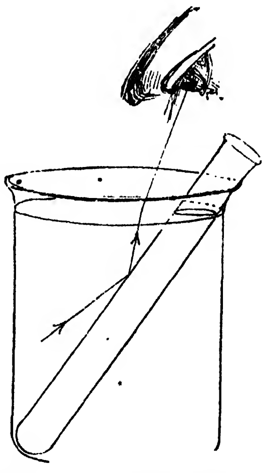


Fig 33.—Total internal reflection.

the critical angle: and the critical angle is the angle whose sine is the reciprocal of the index of refraction into the denser medium. When the angle of incidence is greater than the critical angle we have **total reflection.** The critical angle for diamond is 23° 41′; for flint-glass 38° 41′; for water 48° 30′. Light can-

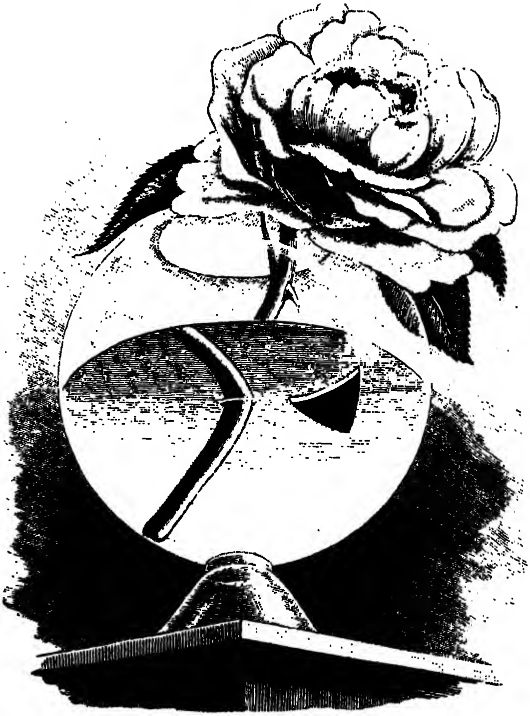


Fig. 34.—Total internal reflection.

not pass out of a diamond at a greater incidence than 23° 41′. It must then be totally reflected internally; and the large proportion of light which is totally reflected in the diamond is the cause of the great brilliancy of that gem. Objects below water become less visbile as we look at them more obliquely.

It is also possible to see that the light is totally reflected. Allow an empty test-tube to lie obliquely in a tumbler of water.

The sides of the tube below the water, viewed from above, appear like brightly polished silver (Fig. 33). Fill the test-tube with water, and the silvery appearance vanishes.

A rose is placed in a glass vase on a mantelpiece (Fig. 34). Looking up at it the eye sees a bright reflection of the stalk in the under surface of the water. A small triangular brick lying on the mantelpiece is seen reflected at the surface of the water as in a highly polished mirror.

Mirage.—Mirage is a phenomenon frequently observed in

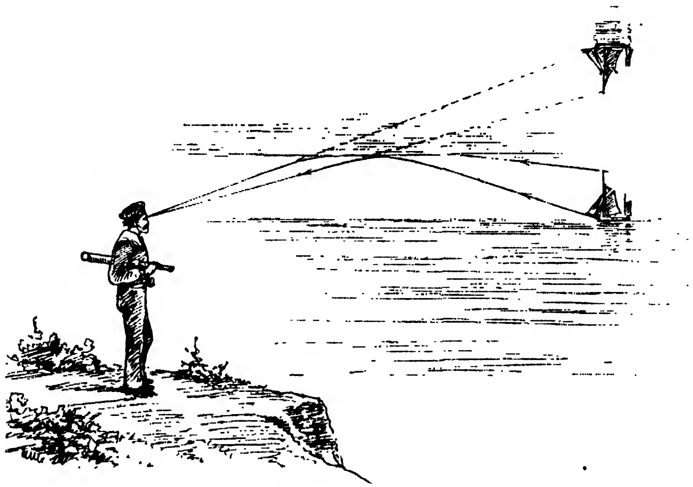


Fig. 35.—Mirage.

the deserts of Egypt and Africa; the traveller sees the reflection of distant objects, palm trees and so forth, in what appears to be a lake of water. This was first explained by Monge, who accompanied Napoleon Bonaparte to Egypt. The surface of the ground being exceedingly and uniformly hot, the air near it becomes highly heated, and decreases in density the nearer it is to the ground. Consequently rays of light incident obliquely are refracted away from the normal, that is upwards, until the angle of total reflection for some layer of air is reached.

They are then reflected and reach the eye in much the same way as if they had been reflected in the surface of a lake of water. The phenomenon can be seen on a small scale by looking along a red hot poker. Light incident at a grazing angle can be seen to be reflected by the layers of thinner air near the poker. A similar phenomenon is occasionally seen over the sea in still hot weather. The image of a distant ship appears in the sky, sometimes inverted, sometimes upright. An American newspaper lately recorded the appearance to the citizens of Buffalo of a sky-picture of the city of Toronto, with its quay and steamers, 60 miles away across Lake Ontario. In all such cases,

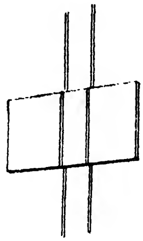


Fig. 36.

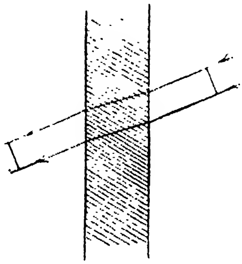


Fig. 37.

Refraction at parallel surfaces.

the air must be still and in even layers. The total reflection takes place in one of the light uppermost layers, and the image is inverted if the rays from different parts of the object cross on the way (Fig. 35).

Refraction at Parallel Surfaces.—In front of two parallel wires or strings hold a piece of thick plate-glass obliquely, as in Fig. 36. The wires seen through the glass appear at the same distance from each other as before, but not in the same straight line with the outside portions of the wires. The fact that the apparent distance between the wires and their apparent thicknesses are unaltered by the glass tells us that the light after passing through the glass emerges parallel to its original direction (Fig. 37).

Geometrical Explanation.—When a ray of light PQ falls on a plate of glass with two parallel surfaces, it is refracted in the direction QQ′, and since the angle NQQ′ is equal to the angle N′Q′Q it will emerge in a direction Q′R parallel to its original direction. Hence objects viewed through a plate of glass whose faces are parallel have their relative positions unaltered.

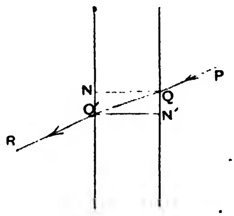


Fig. 38.
Refraction through plate-glass

Images in thick Looking-glass.—Light incident on glass is always partly reflected. This will explain why objects viewed in looking-glass made of thick plate-glass appear to have a number of images.

The first image of the gas flame (Fig. 39) is a faint one, due to reflection at the outer surface of the glass. The second is bright, due to reflection at the silvered back of the glass. After this reflection the light, instead of all emerging, is partly reflected again at the front surface, and once more reflected at the back. In fact it may only finally emerge after one, three, five, seven or any odd number of reflections, of course diminishing in intensity each time. Thus we get a number of images behind one another becoming fainter and fainter.

Fig. 39.—Images in a thick looking-glass.

In Fig. 40 light coming from P may be reflected at the outer surface and appear to come from P_1 (faint), or it may enter the glass by refraction, be reflected at the back of the mirror and emerge parallel to the

first reflected ray, forming an image at P_2 (bright), or it may, instead of emerging, be reflected twice more and form an image P_3 (fainter), and so on.

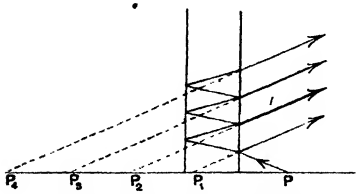


Fig. 40.—Reflection in thick glass.

Total Reflection Prism.—The critical angle for crown-glass is less than 45°. Let ABC (Fig. 41) be a section of a prism of crown-glass made so that ABC = 90°, and the other two angles are each of them 45°. Light falling perpendicularly on the face BC will be totally reflected at the inner surface AC and will emerge

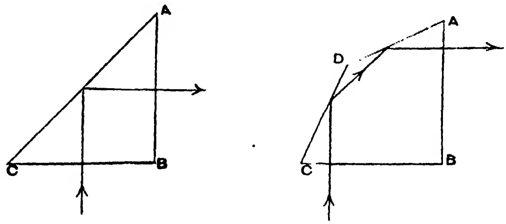


Fig. 41. Fig. 42.
Total reflection prisms.

perpendicular to the face AB. Fig. 42 shows a section of a total reflection prism of another kind, not requiring so small a critical angle. The angle ADC = 135°.

Such prisms are much used in lighthouses.

CHAPTER VI

Refraction through a Prism—Dispersion

Definitions—Minimum Deviation—Dispersion—Spectrum—Newton's Experiment—White Light a Combination of all Colours—Dispersive Power varies in different Substances.

Refraction through a Prism.—A prism is defined to be a solid contained by a number of planes, each of them perpendicular to the same plane, or, which comes to the same thing, parallel to the same straight line, and by two more surfaces which form the ends of the prism. Optically a prism may be considered as a refracting medium partly enclosed between two planes making any angle with one another. The angle between the planes is called **the angle of the prism.** Fig. 43 gives a section of such a prism. The **edge** of the prism, *i.e.* the line of intersection of the two planes, is supposed to be perpendicular to the paper, and therefore the angle BAC may be taken as the angle of the prism. The light is supposed to be incident in the plane of the paper.

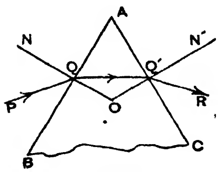


Fig. 43.
Path of ray through a prism.

An incident ray PQ is refracted in the direction QQ′, and on reaching the second surface is again refracted in the direction Q′R.

Minimum Deviation.—In Fig. 44 is shown a prism standing with its edge vertical. Light from a vertical slit with a short

focus lens in front of it falls on the prism and is refracted on to the screen. By turning the prism round, the image of the slit on the screen will be shifted. A certain position can easily be found in which the image of the slit is less bent towards the left than in any other position. When this is found, and the prism rotated in *either* direction, the image moves off to the left. This position is called the position of minimum deviation. Start with the prism turned away from the position of minimum deviation and turn it slowly towards that position. The image of the slit

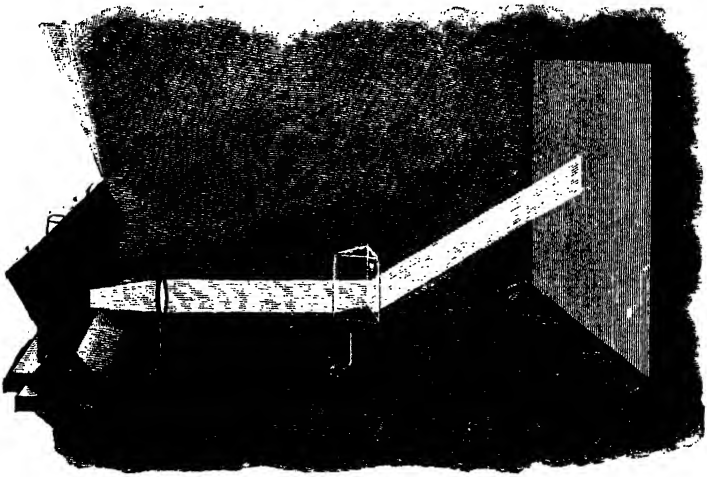


Fig. 44.—Deviation produced by prism.

moves to the right, becomes stationary, and then as you go on turning moves off to the left again. It becomes stationary at the position of minimum deviation in the same way as a stone thrown up in the air is momentarily at rest when it reaches its highest point. A slight turn in the prism at this position produces no noticeable increase of deviation, so a small pencil of rays incident in this position undergoes the same deviation throughout and is not narrowed or widened. The apparent distance of the source of light from the prism is therefore the same as the real distance. It should be noted also that in the

position of minimum deviation the angles of incidence and emergence PQN, N′Q′R (Fig. 43, repeated below) are equal.

The **total deviation** of the ray is the angle between its first and its last directions. At Q (Fig. 43) its deviation is PQN − OQQ′. At Q′ its deviation is RQ′N′ − OQ′Q; hence its total deviation is PQN + RQ′N′ − (OQQ′ + OQ′Q). But OQQ′ + OQ′Q = BAC = i, the angle of the prism. Calling PQN, the angle of incidence, ϕ; and RQ′N′, the angle of emergence, ψ, we have for the total deviation $\phi + \psi - i$. It is found, by the experiment just described and by theory, that this deviation varies with the angle of incidence ϕ, and is least when the light falls so as to make the angle of emergence ψ equal to ϕ. This position is called the position of minimum deviation.

The minimum deviation of a prism is $2\phi - i$, where ϕ is given by the equation $\phi = \mu \sin \frac{i}{2}$ (sin PQN = μ sin OQQ′).

This gives $$\mu = \frac{\sin \phi}{\sin \frac{i}{2}}.$$

If D be the minimum deviation, we have $\phi = \frac{D+i}{2}$,

therefore $$\mu = \frac{\sin \frac{D+i}{2}}{\sin \frac{i}{2}}.$$

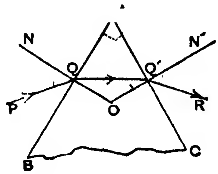


Fig. 43 (repeated).
Path of ray through a prism.

This formula is very useful in finding the refractive index of a substance. A prism is made from the substance, its angle and the minimum deviation of a ray passing through it can be measured with considerable accuracy. The formula quoted above will then give us μ, the refractive index.

Dispersion.—In making the experiment shown in Fig. 44 it will be noticed that the image of the slit is edged with colour, red on one side and bluish-green on the other. If sunlight be used and admitted through a narrow slit into a dark room, and a bottle prism filled with carbon disulphide be used instead of a glass prism (though a glass prism does well enough), the appearance will be far more beautiful and striking. This experiment is perhaps the most beautiful in the whole range of science, and well repays the slight trouble necessary for performing it; a

mirror, placed outside a window so as to reflect the direct rays of the sun into the room, and the prism are all the apparatus required. Fig. 45 gives some idea of the way of obtaining this **spectrum**, a coloured picture of which is opposite p. 598. If a lamp be used, as in Fig. 44, a lens of short focus must be placed in front of the slit so as to give a parallel beam of light. With sunlight the lens is not needed, except where a pure spectrum is required. See Spectroscope, Chapter XII.

Newton's Experiment.—The great experiment, showing that white light consists of light of many different colours, was made by Newton in 1666.[1] He admitted sunlight into a dark room

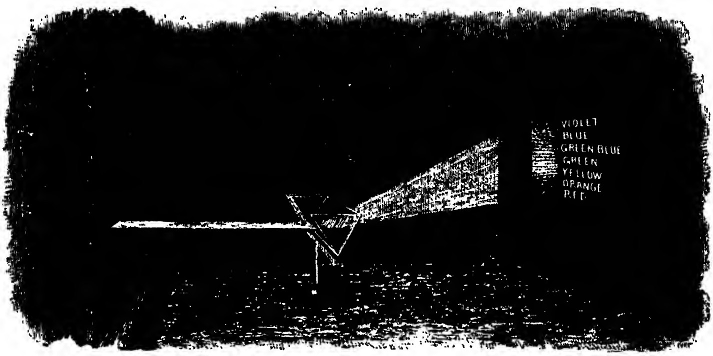


Fig. 45.—The spectrum.

by a small round hole S in a shutter, and caused the light thus admitted to fall on a prism. Instead of getting, as he expected, a white image of the sun thrown on the white screen which he placed to receive the refracted light, he found an elongated image indistinct at the ends, and of different colours, ranging from the least refracted, red, to the most refracted, violet; and with yellow, green, blue in between (Fig. 46). Then by putting a second prism of the same kind in the path of the coloured lights and with its edge at right angles to the edge of the first prism, he found that the coloured light was not split up

[1] For an account of Newton's experiments in his own words, see Preston's *Theory of Light* or Newton's own *Opticks*.

any further, but that as before the violet rays were more refracted than the red, so that the spectrum, as Newton called the coloured band of light, was refracted into the oblique position

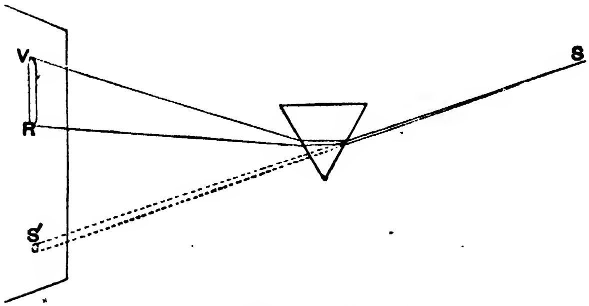


Fig. 46.—Dispersion of white light.

V′R′ instead of VR (see Fig. 47). This separation of white light into different colours is called **dispersion.**

Dispersion Corrected.—Newton concluded from this that sunlight consists of a mixture of lights of all colours, and that white is the combined effect of them all. He confirmed this con-

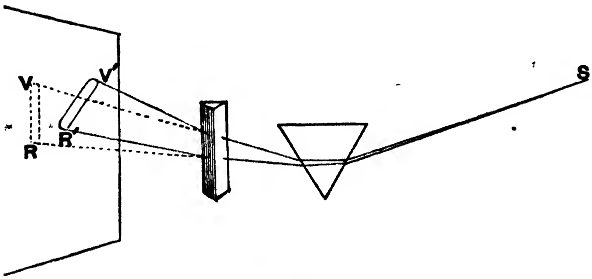


Fig. 47.—Dispersion of white light.

clusion by putting another similar but reversed prism in the path of the dispersed colours and so recompounding them and restoring white light. But he found that the white light so restored was also restored to its original direction. He concluded therefore that this dispersion of the colours could not be got rid of

without getting rid of the refraction as well. In this he was mistaken. Different substances differ widely in their power of dispersion. For instance, carbon disulphide disperses the colours more widely than glass, although its refractive index for yellow light is the same. Hence a narrow prism of carbon disulphide corrects the dispersion of a wider prism of glass without getting

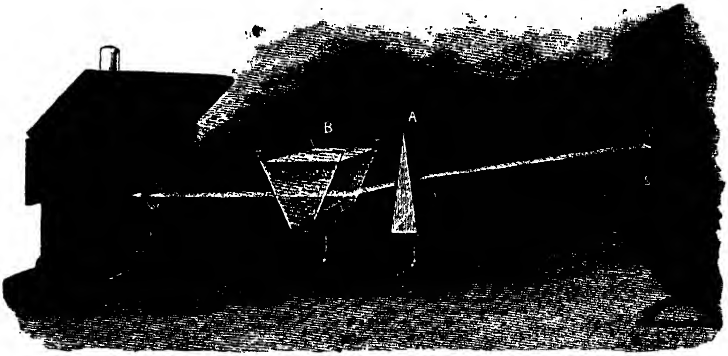


Fig. 48.—Dispersion corrected.

rid of the refraction altogether. The subject is further discussed on p. 601.

The dispersive power of water is smaller. Fig. 48 shows a narrow glass prism A correcting the dispersion of a water prism B while leaving enough refraction to shift the image of the slit from S to S'.

CHAPTER VII

Reflection and Refraction at Spherical Surfaces—The Rainbow

Definitions—Images in Concave and Convex Mirrors—Magnification—Refraction at Spherical Surface—Rainbow—Primary and Secondary Bows.

Reflection at Spherical Surfaces.—The normal, *i.e.* the perpendicular to the tangent plane, at any point on the surface of a sphere passes through the centre of the sphere. A spherical mirror is a mirror whose reflecting surface is a portion of the surface of a sphere. If the inner surface is used for reflecting, the mirror is called **concave**; if the outer surface is used the mirror is called **convex**. In general only a small portion of the surface of the sphere is used, and its boundary is usually circular (Fig. 49).

Fig. 49.—Concave and convex surfaces.

The centre of curvature of the mirror, or **centre** *of the mirror,* is the centre of the sphere of which the mirror is a part.

The middle point of the reflecting surface is sometimes called *the* **pole** *of the mirror.*

The straight line joining the centre of curvature to the pole is called *the* **principal axis** *of the mirror.*

Principal Focus.—When a small parallel pencil of rays is incident on a concave spherical mirror *directly,* that is parallel to the axis, the rays all converge to a point on the axis called the

principal focus. Let C be the centre of a concave spherical mirror, and A its pole (Fig. 50). Let a ray PQ parallel to the axis CA fall on the mirror at the point Q. Join CQ. The angle of reflection being equal to the angle of incidence, the reflected ray will be QF, the angle CQF being equal to the angle CQP. But since PQ is parallel to CA, angle PQC = QCF.

$$\therefore \text{FQC} = \text{QCF}. \qquad \therefore \text{FQ} = \text{FC}.$$

But since Q is very close to A, FQ = FA nearly.

$$\therefore \text{FA} = \text{FC}.$$

So the principal focus F is half-way between the centre and the pole. When the mirror is convex, the same thing is true; only

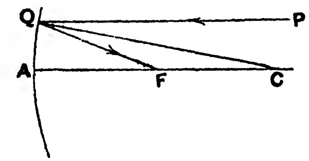


Fig. 50.—Principal focus, real.

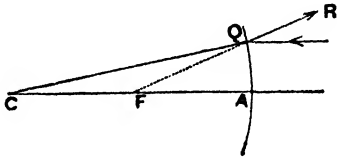


Fig. 51.—Principal focus, virtual.

in this case the reflected rays do not actually pass through the point F, which is therefore a **virtual focus** (Fig. 51).

The rays which fall on the outlying portions of the mirror do not when reflected pass accurately through the point F, only near to it. In fact all the reflected rays are tangents to a certain surface, called the **caustic surface**, of which a section, which we may call a **caustic curve,** is given in Fig. 52.

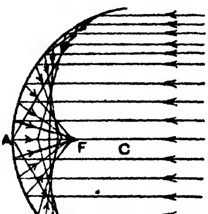


Fig. 52.—Caustic curve.

A candle-flame, reflected at the inside of a bright silver napkin-ring, throws on a white table-cloth an image in the shape of the curve shown in Fig. 52.

It will be noticed that except for the outside rays the deviation from the point F is slight, and for rays near the axis CA

so slight as not to be noticeable. This deviation from the exact focus is called **spherical aberration.** If the section of the surface be a parabola instead of an arc of a circle, all the rays of a pencil parallel to the principal axis are reflected accurately through a single focus.

Construction for finding the Image of an Object in a Spherical Mirror.—As before, let C be the centre, A the pole of the mirror, and let PQ be two points on the object whose image

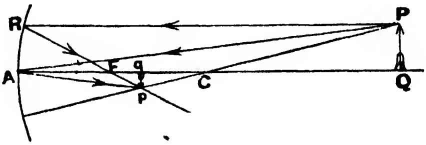


Fig. 53.

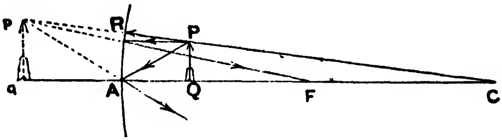


Fig. 54.

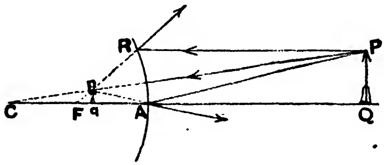


Fig. 55.
Images in spherical mirrors.

is to be found, Q being on the axis of the mirror (Figs. 53, 54, 55). To find the image of the point P, it will be sufficient to find the point of intersection of two rays from P after reflection at the mirror. Draw PA and make the angle pAC equal to PAC. Then draw PR parallel to the axis. By the previous article, the reflected ray must pass through the principal focus F. Join RF and produce it till it meets Ap in p. Then p will be the image of P, and pq the image of PQ. In Fig. 53 the image is real

and inverted. In Fig. 54, where the object is situated between the principal focus and the mirror, the image is *virtual* and upright. In Fig. 55, where the mirror is convex, the image is *virtual* and upright.

Notice also that the image p can be found without any measurement of angles. For a ray incident through the centre C is reflected back along its own path. Hence the line joining P to C must pass in every case through p. This is the simplest method of finding the image.

Magnification.—The magnification is the ratio of the linear dimensions of the image to those of the object. In the foregoing cases the magnification is $\frac{pq}{PQ}$. But since the angles pAq, PAQ are equal—

$$\frac{pq}{PQ}=\frac{Aq}{AQ},$$

therefore the magnification is the ratio of the distance of the image from the mirror to the distance of the object from the mirror.

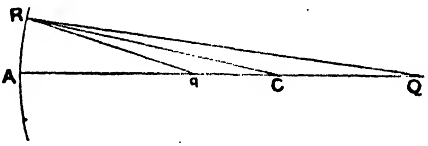


Fig. 56.—Conjugate foci.

Conjugate Foci.—With a spherical mirror it is immaterial which of the radii from the centre is taken as the axis. In Fig. 53, by taking as axis some radius near to AC, it may be shown that q is the image of Q. Two such points, each situated on the same axis, the rays from one of which are brought to a focus at the other, are called *conjugate foci.*

Formula connecting the distances of two Conjugate Foci from the Mirror—Focal Length.—Let Q and q be two conjugate foci (Fig. 56). Then R being a point on the mirror, angle CRQ=CRq, by the law of reflection. Then (Euc. VI. 3)—

$$\frac{Cq}{CQ}=\frac{Rq}{RQ}=\frac{Aq}{AQ},$$

if R is near A. Then Aq, AC, AQ form a harmonical series.

If u represent AQ the distance of the object, v the distance of the image Aq, and r the radius of the sphere, this gives us—

$$\frac{1}{u}+\frac{1}{v}=\frac{2}{r}.$$

Also $\frac{r}{2}=$ AF the distance of the principal focus from the mirror, the *focal length* of the mirror. Hence

$$\frac{1}{u}+\frac{1}{v}=\frac{1}{f}.$$

Refraction at a Spherical Surface.—A ray PQ incident on a spherical refracting surface whose centre is C (Fig. 57) will be

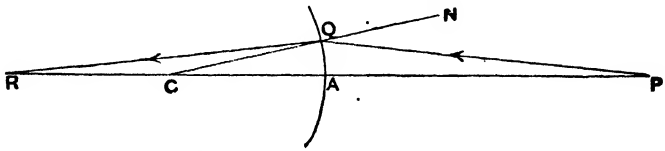


Fig. 57.—Refraction at spherical surface.

refracted in a direction QR given by the relation $\frac{\sin PQN}{\sin CQR}=\mu$ the refractive index of the medium. When we have a small pencil

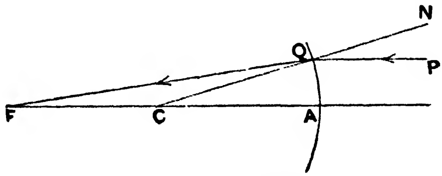


Fig. 58.—Refraction of parallel rays.

of rays parallel to the axis CA of the surface, they will be refracted to a focus F (Fig. 58).

Let AC $=r$ and AF $=f$. As before—

$$\mu=\frac{\sin PQN}{\sin CQF}=\frac{\sin ACQ}{\sin CQF}=\frac{\sin FCQ}{\sin CQF}=\frac{FQ}{CF}=\frac{AF}{CF}\text{ approximately,}$$

$$\therefore\ \mu=\frac{f}{f-r},$$

$$\therefore\ f=\frac{\mu r}{\mu-1}.$$

The Rainbow.—Refraction at a single spherical surface is chiefly of interest in the case of the rainbow. From very early

times this phenomenon has been known to be due to the refraction and reflection of the sun's light falling on drops of water. The observer of a rainbow always has his back to the sun, so that a straight line from the sun to his head would if produced pass through the centre of the rainbow. A rainbow may be often seen in the spray from a waterfall or from the paddles of a steamer. The geometrical explanation of the phenomenon is due to De Dominis, Descartes, and Newton, the last-named giving the reason of the colours.

Rays of light from the sun may be considered as parallel, because the sun is so far away. Let SP (Fig. 59) be a ray

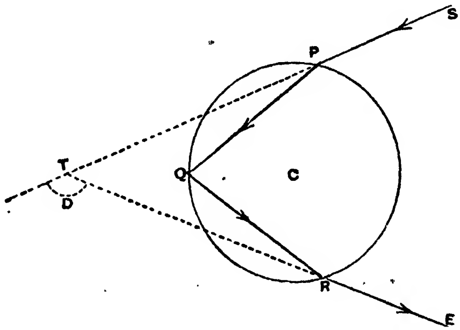


Fig. 59.—Refraction and reflection in rain-drop.

from the sun entering a spherical rain-drop at P. It will be refracted, and, on again reaching the surface of the drop, some of the light will be reflected and pass out again at R.

The incident and emergent rays are produced in Fig. 59 to meet at T. The change in the direction of the light is given by the obtuse angle D, which is called the **deviation**. This is least when the acute angle STE is greatest, that is, STE is greatest in the position of 'minimum deviation.' In Fig. 60 are shown a number of parallel rays falling on different points on the surface of a spherical rain-drop with their paths after one internal reflection. The ray SPQRE is in the position of **minimum deviation.** The rays near it on each side of it, those

falling within the shaded area, emerge very nearly in the same direction. The further a ray is from SP the greater will be its

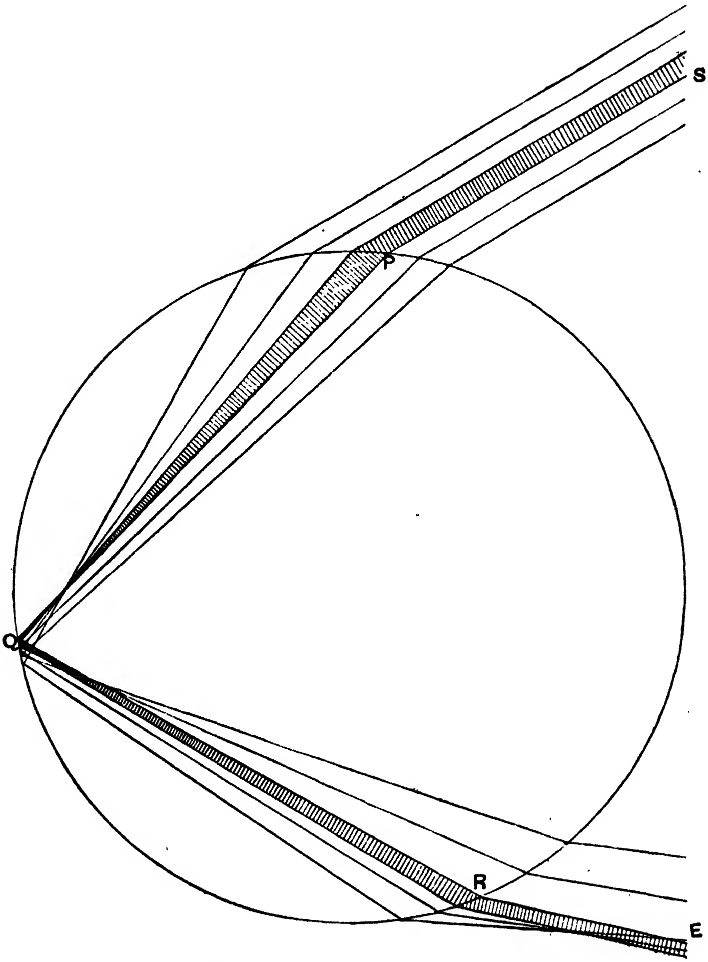


Fig. 60.—Parallel rays falling on rain-drop.

deviation, and it is only in the direction RE that the eye will be attracted by a sense of brightness. The angle between SP

and RE is about 42°. An observer facing a rain-cloud with the sun shining on it from behind him will receive a noticeable quantity of light from all drops in the cloud so situated that the line joining them to his eye makes an angle of about 42° with the line joining them to the sun. These drops all appear to lie on a circle whose centre is a point exactly opposite the sun, and the angular radius of the circle is evidently 42°. This is the value of the angle STE (Fig. 59) for red light. For violet light it is about 40°, and for other colours it has values intermediate between these, so we see in the rainbow a set of concentric circles of all the colours of the spectrum, red being outside, then orange, yellow, green, blue, indigo, and violet. The angular radius of the rainbow as obtained by calculation from the laws of refraction and reflection agrees exactly with observation.

Secondary Bow.—Often another and fainter rainbow is visible outside the chief or primary bow. This second bow is

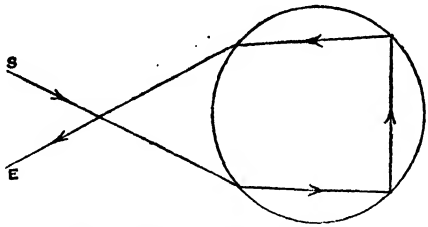


Fig. 61.—Formation of secondary bow.

due to the sunlight undergoing two internal reflections in the rain drops, as shown in Fig. 61. The *secondary* bow, as it is called, has the colours reversed, and less brilliant. Sometimes a third bow is seen when the sun is very bright, just outside the secondary bow; this is a quintary bow, caused by five internal reflections. The first nineteen bows have been seen in a laboratory.

Fig. 62 gives some idea of the position of the bows. The shadow of the observer's head forms the centre of a rainbow; or, more exactly, a line through the observer's eye parallel to the direction of the sun's rays forms the axis of the bow. This line is inclined to the horizontal at an angle equal to the

sun's altitude (Fig. 62). Four drops are drawn as specimens of those which reflect the extreme colours in each bow. For example, those which reflect the violet colour in the primary

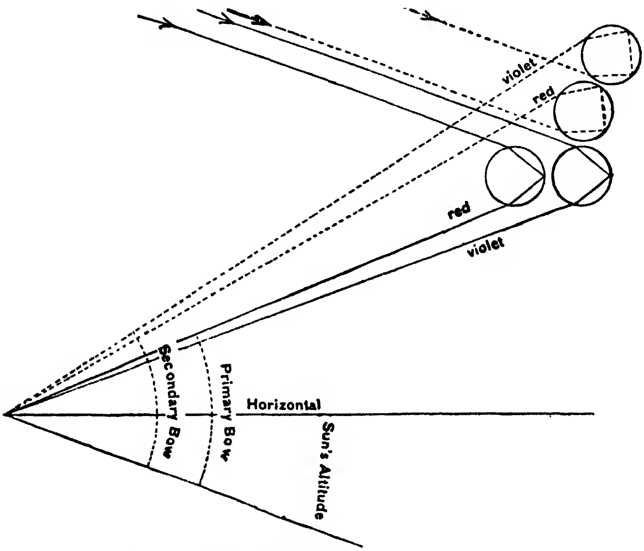


Fig. 62.—Position of rainbows, primary and secondary.

bow lie on a cone whose generatrix forms an angle of 40° with the axis of the bows, as shown. The angular radius of the red in the secondary bow is about 50°, and of the violet 53°.

The natural phenomenon of the rainbow is much more complex than the simple arc of prismatic colours which this brief description provides for. 'Spurious bows,' the colours seen on the inside edge of the primary bow and other variations, have formed the subject of a recent investigation by Mr. J. M. Pernter (see *Nature*, January 27, 1898). They are due to interference phenomena "dependent upon the ratio of the radius of the drops to the wave length of light. The greater the drops, the more the spurious bows; a partly white bow is produced by drops of 0·06 mm., and when the drops are still smaller, a real white bow, with orange-yellow and blue margins, is the result."

CHAPTER VIII

LENSES

Definitions—Images formed by Convex and Concave Lenses—Focal Length—Method of finding Focal Length—Lighthouse Lenses—Spherical Aberration—Chromatic Aberration—Achromatic Lenses and Prisms.

Lenses.—A **lens** is a piece of glass or other refracting medium bounded by two surfaces, which are usually portions of spheres.

A representation of the different types of lenses is given in

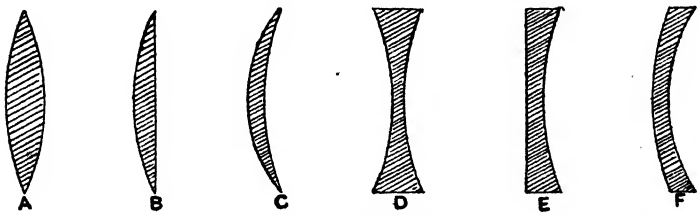


Fig. 63.—Different forms of lenses.

Fig. 63. A, B, C are converging or convex lenses, and D, E, F are diverging or concave lenses.

A is a **double convex** lens.
B ,, **plano-convex** ,,
C ,, **concavo-convex** ,, or a **convex meniscus.**
D ,, **double-concave** ,,
E ,, **plano-concave** ,,
F ,, **convexo-concave** ,, or a **concave meniscus.**

In lenses which have one plane surface, this may be looked on as the surface of a sphere whose radius is infinite.

The **axis of a lens** is a straight line joining the centres of the two surfaces, or in the case of the plano-lenses, the line through the centre of the spherical surface perpendicular to the plane.

Principal Focus.—A pencil of parallel rays falling on a convex lens and parallel to its axis will converge after passing

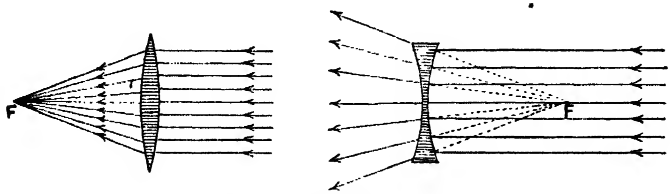


Fig. 64.—Principal focus of lens.

through the lens, and the rays will all very nearly pass through a certain point on the axis. If the lens is concave the pencil will be made to diverge, but will appear to diverge from a point on the axis (Fig. 64). In either case this point F is called the *principal focus* of the lens.

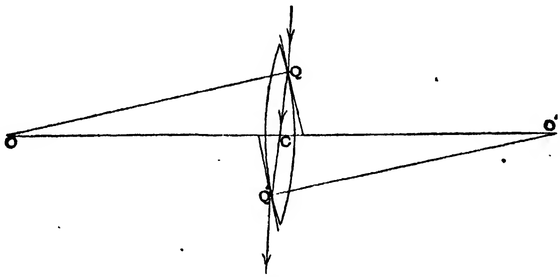


Fig. 65.—Optical centre of lens.

The distance between the focus and the lens is called the **focal length** of the lens.

Optical Centre of a Lens.—Let O and O′ be the centres of the two surfaces of a lens (Fig. 65). Draw two parallel tangent planes at Q and Q′. A ray which passes in the lens along the path QQ′ must emerge parallel to its original direction, for it has

been refracted at two parallel surfaces (p. 536). By similar triangles

$$\frac{OC}{O'C}=\frac{OQ}{O'Q'}=\frac{R}{R'},$$

the ratio of the two radii. Hence C is a fixed point, no matter what the positions of the points Q and Q′. So we find for every lens a fixed point C on its axis, all rays passing through which emerge parallel to their original directions. This point is called the optical centre, or shortly, the **centre** of the lens.

Thickness of a Lens.—Often the thickness of a lens is very small compared with its focal length. In most of the diagrams which follow, the lens is regarded as lying in a vertical plane through C (Fig. 66), and the curved lines are put in merely to indicate the shape of the lens.

Conjugate Foci.—A pencil of rays from any point near the

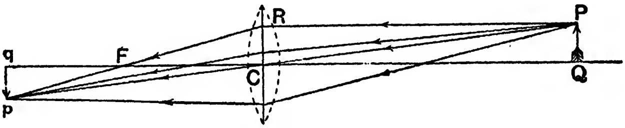


Fig. 66.—Convex lens—real image.

axis of a lens, after passing through the lens, converges to or appears to diverge from another point also near the axis. Such two points are called *conjugate foci*, and the rays of a pencil from either point will after refraction pass or appear to pass through the other.

Images formed by Convex Lenses.—In finding the image of a point P formed by a lens (see Figs. 66, 67) two rays should first be drawn. The ray through the optical centre C has its direction unchanged, and the ray PR parallel to the axis is refracted so as to pass through the principal focus F.

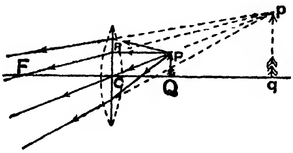


Fig. 67.—Convex lens—virtual image.

The intersection of these rays gives the image of P, and the other rays can then easily be drawn. Fig. 66 shows a real inverted image formed by a convex lens. Fig. 67 shows a virtual upright

image formed by a convex lens—*virtual* because the refracted rays do not actually pass through the point p, but only appear to diverge from it, the dotted lines not being parts of the rays, but only the rays produced backwards. The image of Q falls at q, on the axis, and in the same vertical plane as p. This should be verified by experiment.

Image formed by a Concave Lens.—Using the same construction, it will be seen that rays from PQ will after refraction appear to come from a virtual upright image pq (Fig. 68).

Magnifying Power of a Lens.—The magnifying power is the ratio of the linear dimensions of the image to those of the object. Thus in Fig. 67 the magnifying power is—

$$\frac{pq}{PQ}=\frac{Cq}{CQ}=\frac{v}{u},$$

v and u being the distances of the image and object respectively from the lens.

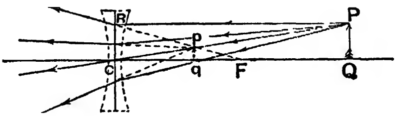


Fig. 68.—Concave lens—virtual image.

Formula connecting Conjugate Foci. — *N.B.* — Distances are measured from the lens; those measured on the side from which the light comes are taken as positive, on the opposite side negative. With a convex lens, parallel rays are brought to a focus on the opposite side of the lens. Hence the focal length of a convex lens is always negative. If the image formed by the lens is a real one, and therefore on the opposite side of the lens to the source of light, its distance from the lens must be taken as negative.

Let u, v, f represent the distances of the object and its image and the focal length of the lens respectively.

In Fig. 68 $\frac{pq}{PQ}=\frac{Cq}{CQ}$; also $\frac{pq}{PQ}=\frac{pq}{RC}=\frac{Fq}{FC}$.

Hence $\frac{Cq}{CQ}=\frac{Fq}{FC}$ $\therefore$ $\frac{v}{u}=\frac{f-v}{f}$ $\therefore$ $\frac{1}{v}-\frac{1}{u}=\frac{1}{f}$.

This formula, with due regard to sign, will be found to agree with Figs. 66 and 67.

To find the Focal Length of a Lens.—For this purpose an optical bench is used. This is a straight bar, graduated in inches or centimetres, on which stands can be made to slide, supporting the lens, **the source of light** (a candle or a strongly-illuminated needle point), and the screen on which the image of the **source of light** is to be received. Fig. 69 gives a representation of this arrangement. The lens is shifted about, and for each position of the lens the screen is shifted until a sharp inverted image of the candle flame is formed on it. The distances of the candle and the screen from the lens are then measured. Suppose them to be 10 and 20 inches respectively. Using the formula—

$$\frac{1}{v}-\frac{1}{u}=\frac{1}{f},$$

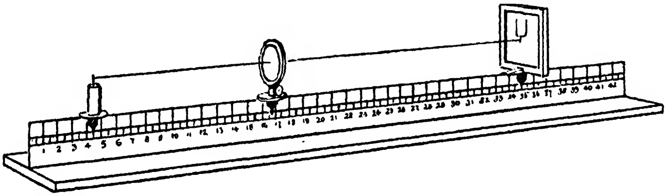


Fig. 69.—Optical bench.

and remembering that v is negative, we have—

$$-\frac{1}{20}-\frac{1}{10}=\frac{1}{f}.$$

$$\therefore \quad f=-\frac{20}{3}=-6\tfrac{2}{3} \text{ inches.}$$

A large number of such measurements are made. They will be found to agree closely, and the value of f, the focal length, is calculated from the average of all the observations. The greater the convexity or the concavity of a lens, the less will be its focal length. When the two surfaces of the lens are parallel, the convexity is of course zero, and the focal length is infinite; a parallel pencil emerges parallel.

Lighthouse Lenses.—A lighthouse should throw a strong parallel beam of light over the sea: the rays should be parallel in order that a distant point may receive as many rays as possible.

For this purpose the source of light is placed in the focus of a convex lens, and the rays after passing through the lens emerge parallel to one another. A large lens is required to catch as much of the light as possible; but as a large lens must be thick, a certain quantity of the light will be absorbed by it. To avoid this, Fresnel invented échelon or lighthouse lenses, of which a section is shown in Fig. 70. In the centre is an ordinary plano-convex lens, which is surrounded by a set of plano-convex

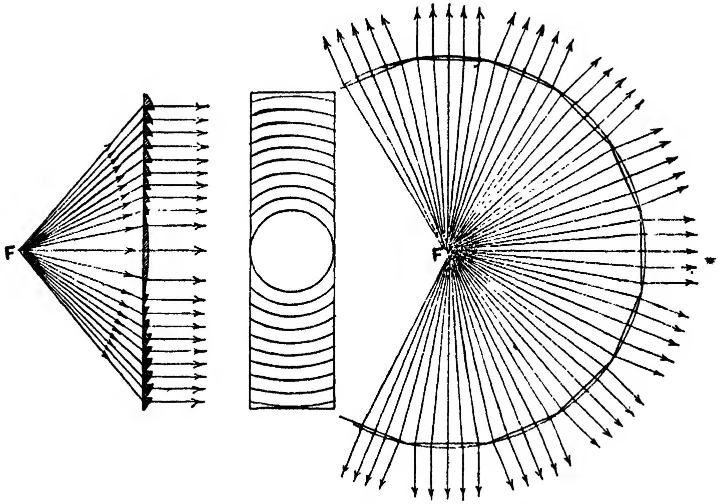


Fig. 70.—Section. Fig. 71.—Front view. Fig. 72.—Plan.
Lighthouse lenses.

rings, all of the same focal length. Fig. 71 gives a front view of the arrangement. It will be noticed that the rings are not complete, there is only an arc of each ring above and below the central lens. This is because such a system of lenses throws a parallel beam in one direction only, and it is necessary to illuminate several points of the horizon. So a number of faces like that in Fig. 71 are arranged symmetrically round the light. Fig. 72 shows the arrangement of the dioptric apparatus at the South Foreland. Sixteen such faces are arranged round the

lamp and the intensity of the beam of light is about six million candles. If the lenses were fixed, only sixteen points of the horizon would be illuminated; but the system of lenses revolves round the lamp once in eight minutes, giving one flash every half-minute. This apparatus was formerly at St. Catherine's Lighthouse, Isle of Wight; a new one has taken its place there having four panels only, giving one flash every five seconds, and it is (1906) probably the most powerful electric beam in the world. The intervals of the flashes at different lighthouses enable the mariner to distinguish between them, and to know his position.

Spherical Aberration.—As in the case of reflection at spherical mirrors, so in lenses we have a certain amount of spherical aberration due to the rays which fall near the edge of the lens not being accurately brought to the same focus as

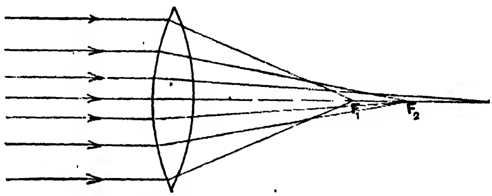


Fig. 73.—Spherical aberration.

those which pass near the centre. This is shown in an exaggerated form in Fig. 73. The rays falling near the edge of the lens are brought to a focus at F_1 and those near the centre at F_2. A defect of this kind makes the images formed by the lens blurred and indistinct. It may be removed by altering the curvature of the faces, or by using systems of lenses in which each lens helps to counteract the defects of the others. Or the outer rays may be shut off by using diaphragms or stops, which are opaque screens with holes cut in them. Sometimes it is the outer rays that are wanted and circular stops are used to cut off the rays near the centre. A system of lenses in which spherical aberration is done away with is called an **aplanatic** system (ἀ not, πλανάω *planao*, I wander).

* **Chromatic Aberration.**—The focal length of a lens depends

on the refractive index of the substance used for the lens. Given two lenses of the same size and shape but of different material, the lens of higher refracting power will have the shorter focus. Now the refractive index varies slightly with the colour of the light. Hence the same lens will have different focal lengths for light of different colours. The violet rays are more refracted than the red. In Fig. 74 is shown a parallel pencil falling on a lens. The violet rays are brought to a focus at V and the red rays at R, and the blue, green, and yellow rays at points between V and R. A screen at the point A will show a circular patch of light edged with red, while a screen at B will show a patch of light edged with blue or violet. This defect, possessed by all simple (*i.e.* single) lenses, is known as *chromatic aberration.* Newton, as we have said, supposed the dispersion of colours to be proportional to the refraction, and consequently held that no

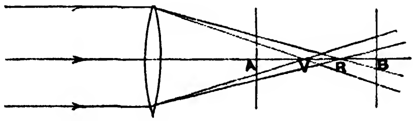


Fig. 74.—Chromatic aberration.

arrangement could be made for getting rid of the coloured edging without also getting rid of the refraction. This led him to invent his reflecting telescope; for light of every colour is reflected in the same way, and there is no chromatic aberration among rays concentrated by a reflector. After his death his views were proved incorrect, and achromatic lenses were invented.

Achromatism.—Absence of colour (ἀ not, χρῶμα *chroma*, colour). On p. 544 a description is given of an experiment showing that dispersion can be corrected without getting rid of refraction altogether. Newton himself made a similar experiment with a glass prism immersed in a water prism with their refracting angles opposite; but he found achromatism only when there was no alteration in the course of the ray. Newton frequently used lead in his water prisms, and this increases the dispersive power of water. This is the most probable explanation of his mistake

(see Professor Lewis Wright's *Light*). In 1757, Dollond, a London optician, repeated Newton's experiment and obtained an opposite result. This led him at once to the discovery of a combination of lenses which got rid of chromatic aberration. His arrangement is shown in Fig. 75. A is a double convex lens of crown-glass, and B a double concave lens of flint-glass. Flint-glass separates the colours more widely than crown-glass; in other words, flint-glass has a higher dispersive power than crown-glass, so that a weak flint-glass lens separates the colours as widely as a much stronger crown-glass lens. The concave flint-glass lens makes the light diverge, separating the colours at the same time. The convex crown-glass lens makes the light converge, separating the colours in the opposite way; and if it is to correct the dispersion of the flint-glass lens it must be much stronger in its refracting power, that is to say, it must make the light converge more than the flint-glass lens makes it diverge, and the net result will be light, convergent as if from a single convex lens of strength equal to the difference of the two lenses, but devoid of colour. Such a lens or system of lenses is called **achromatic**. The lenses of good telescopes and opera-glasses are made achromatic in this way.

Achromatic lens.
Fig. 75.

An achromatic prism can be made by combining two prisms of crown- and flint-glass respectively. A thin prism of flint-glass B (Fig. 76) is sufficient to counteract all the dispersion of the crown-glass prism A; while the refraction, though lessened by the prism B, is not done away with altogether. The red and violet rays emerge in the same direction. It does not follow that the intermediate colours, yellow, green, etc., emerge in the same direction. In fact a double lens or prism of the above kinds can be made absolutely achromatic for two colours only.

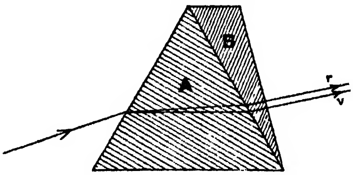


Fig. 76.—Achromatic prism.

CHAPTER IX

The Eye

Description of the Eye—Why we have Two Eyes—Stereoscope—Duration of Impressions—Defects of Vision—Least Distance of Distinct Vision.

The Eye.—Before considering the construction of the various instruments which are used as aids to sight, it is necessary to form some idea of the mechanism of the instrument they are intended to help. The eye acts very similarly to a photographic camera. A lens just behind the **pupil** of the eye (which is a hole admitting light) forms an inverted image of the objects, from which the light comes, on a plate or screen at the back of the eye, called the **retina**. From the retina the optic nerve conveys the impression of sight to the brain.

The eye is very nearly a sphere (Fig. 77). Its outer coating, the **sclerotic**, which is the white of the eye and its continuation, is horny and opaque; but it has a circular transparent portion *cc* (called the **cornea**) which is more curved than the rest of the eye. Through this transparent portion can be seen the coloured part of the eye, the iris, which is the visible part of a second coat extending all round the eye

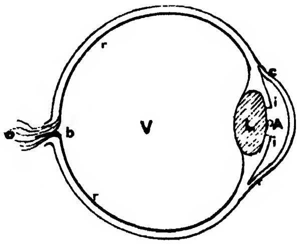


Fig. 77.—The human eye.

inside the sclerotic, which is called the **choroid**. The **iris**, *ii* in the figure, has a circular hole in it, *p*, called the **pupil**. The

iris contracts and expands automatically, so as to admit less or more light through this hole, the pupil, into the interior of the eye. In the dark the pupil expands, and in strong light contracts to a very marked extent. With cats the pupil is not circular but elongated. Just behind the pupil is a transparent lens L called the **crystalline lens,** whose curvature, especially that of the front surface, can be increased by relaxing the tension of the ligament which connects it to the choroid. The space between the lens and the cornea is filled with a transparent fluid A called the **aqueous humour,** and behind the lens is another transparent fluid, the **vitreous humour,** V. The refractive indices of these humours are very nearly the same as that of water, while the crystalline lens has a slightly higher index. The back part of the choroid is covered with a black

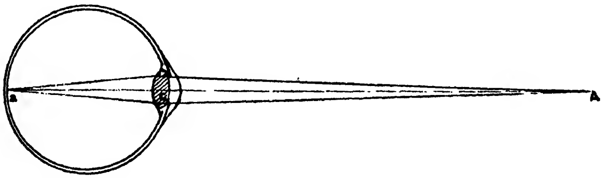


Fig. 78.—Pencil of rays entering eye.

substance, the **pigmentum nigrum,** and over this is a semi-transparent network of nerve fibres *rr*, an extension of the **optic nerve** *o*, which is connected with the brain. This film of fibres is called the **retina,** and on it the images of things seen are formed. In the centre of the retina, slightly inside the entrance of the optic nerve, is the **macula lutea** or **yellow spot,** on which is formed the part of the image most distinctly seen. Just where the optic nerve enters is a small depression *b*, which is insensible to light, having none of the microscopic rods and cones which cover the rest of the retina. This depression *b* is known as the **blind spot.** Fig. 78 shows a pencil of rays from a single luminous point A passing through the pupil (which limits the size of the pencil), and brought to a focus on the retina at *a*. Here C is the centre of the crystalline lens. If the eye were

looking intently at A, *a* would be formed on the yellow spot. Fig. 79 shows the formation of the image of an object AB on the retina. Only the central ray, or axis, of each pencil

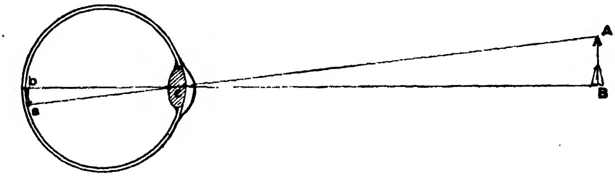


Fig. 79.—Formation of image on retina.

has been drawn in this case. Notice that the image is inverted. Fig. 80 shows the two eyes looking at the same object. The angle between the two axes BAC is called the optic angle, and

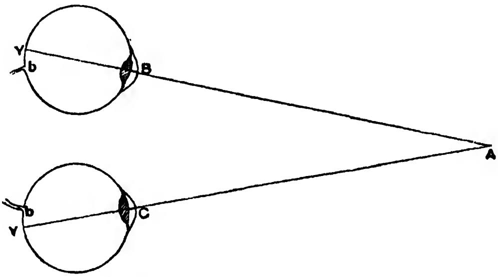


Fig. 80.—Binocular vision.

decreases as the object gets farther away. Fig. 80 also shows the relative positions of the yellow spot Y and the blind spot *b*.

The existence of the blind spot can be proved by the help of Fig. 81. Hold the book with the little cross exactly opposite

Fig. 81.—To prove the existence of the blind spot.

the right eye, and close the left eye. Then look steadily at the cross, moving it inwards from a distance of about a foot. When the right distance has been obtained, the black dot becomes invisible. Its image falls on the blind spot in the retina.

Why we have Two Eyes.—The two eyes look at the same object from slightly different points of view, and so enable us to judge of the distance of objects, and to receive the impression of the solidity of objects. The difficulty of judging distance with one eye only will be manifest to any one who tries to thread a needle with one eye shut. To illustrate the two views given by the two eyes which combine to give one impression to the brain, take a small solid object, say a die, and place it with one of its faces directly opposite to you at a distance of 8 inches or so. The solidity of the cube will be apparent, and if first one eye is closed and then the other, the right eye will see a foreshortened view of the right-hand face, and the left eye will see the left-hand face.

Look at a distant vertical line, as a window bar. Then hold up a pencil about a foot away immediately between your face and the window bar. Look at the pencil, and you will seem to see two distant window bars. The left eye sees the window bar to the left of the pencil, and the right eye to the right of it; and a double impression is thus conveyed to the brain. As a rule one eye is slightly stronger than the other; and it can easily be found which gives the stronger impression to the brain. Hold up a ring and look at a distant object through it with both eyes, the ring being at arm's length. Then shut each eye in turn and it will be found that one eye, usually the right, sees the distant object through the ring, while with the other eye the object shifts to the side. The eye which gives the same view as both eyes together is the stronger, the master eye.

Stereoscope.—By drawing two views of the same object as seen by each eye and placing these views side by side, and making some arrangement by which the right eye looks at the right-hand view only, and the left eye at the left-hand view only, we can convey to the brain the impression that we are looking at a solid object. In Fig. 82 are shown two views of an extinguisher. If a card be held between the figures and they are looked at steadily, one with the right eye, the other with the left, in a few seconds the two views will combine into

one, giving a strong appearance of an actual extinguisher, or what artists call 'a relief' of the extinguisher. An instrument for enabling the eyes to combine two such pictures easily is called a stereoscope. The rays passing through the edge of a lens are bent towards the thicker part of the lens. Hence a piece of a lens may be used for shifting the apparent position of an object. The ordinary stereoscope is made by cutting a convex lens in half, putting the two halves with their edges

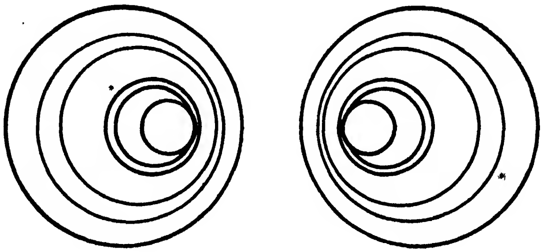


Fig. 82.—Stereoscopic picture.

towards each other, and arranging that the right eye R (Fig. 83) should look through one half at a picture A_1B_1 and the left eye L through the other half at a picture A_2B_2 of the same object, taken from a slightly different point of view. Both lenses will give an enlarged picture in the position AB, which will have the appearance of relief, owing to the slightly different relative positions of the objects in the two views.

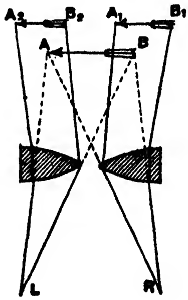


Fig. 83. Stereoscopic images.

Duration of Impressions on the Retina.—When a glowing match is whirled rapidly in the air, the eye can only distinguish a circle of light. The spokes of a wheel rotating rapidly cannot be made out; but when the wheels of a carriage driven in the dark are illuminated suddenly by a flash of lightning, each individual spoke can be clearly made out. This is due to the fact that each impression given to the retina remains for an appreciable

time. In the case of the spark revolving rapidly the impression of light at any point in the circle remains until the spark comes round again, and so a permanent bright circle is seen. The average duration of the impression is $\frac{1}{10}$ of a second; but it varies with different people, and with the strength of the light. Helmholtz found the duration of the impression made by a piece of white paper to last *with undiminished strength* for $\frac{1}{48}$ of a second. In the kinetoscope and kindred instruments, photographs of things in motion are presented to our eyes at the rate of 30 to 40 per second, and the illusion is complete.

The total duration with decreasing strength is much greater. With bright light, like that from a window or the sun, the impression lasts for some minutes, and goes through many changes of colour before it fades. The experiment can easily be made by looking steadily at a bright object and then shutting the eyes.

Accommodation.—It has been mentioned that the crystalline lens can have its curvature altered so as to view near or distant objects. This alteration of curvature is called **accommodation.** When a normal eye is at rest it is in focus for distant objects, *i.e.* for parallel rays, so that the principal focus of the eye lies on the retina. There is a sensation of effort when we look at a near object after looking at a distant one. When we turn to a distant object from a near one, the sensation, if any, is one of relief or relaxation (Foster's *Physiology*). The effort consists in the contraction of the ciliary muscle, which pushes forward the front part of the eye, and allows the suspensory ligament of the crystalline lens to relax its tension, and the lens itself to increase in curvature. The relaxing of the ciliary muscle tightens the ligament again, and the lens is pulled flatter.

Defects of Vision.—Spherical aberration in the eye is corrected by the iris, which acts as a stop, allowing only the central rays to reach the crystalline lens. There is no arrangement in the eye to correct dispersion of colours, and consequently the eye is **not achromatic**; but it needs somewhat refined means to find this out. It can be shown by holding a page of

small print in the dispersed light from a prism, as that in Newton's experiment (p. 542). If the print in the yellow light is distinct, that in the red or the blue will appear indistinct, owing to the eye requiring a slightly different focussing for light of different colours. This defect is common to all eyes.

Short-sightedness or Myopy (*μύω ὤψ, muo ops*, closing the eyes, *i.e.* short-sighted).—In some persons the natural focal length of the eye is too short, and the power of accommodation cannot bring the images of distant objects on to the retina. In such cases only very near objects can be seen distinctly, and the person is **short-sighted**. This defect can be counteracted by concave lenses placed in front of the eyes, which make up for the convexity of the cornea or crystalline lens.

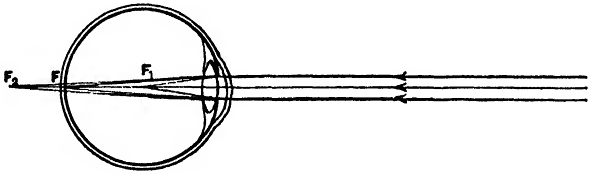


Fig. 84.—Long and short sight.

Fig. 84 shows the position of the principal focus of the crystalline lens and cornea—

F for a normal eye,
F_1 for a short-sighted eye,
F_2 for a long-sighted eye.

The displacements of F_1 and F_2 are exaggerated for the sake of clearness.

Long-sightedness or Hypermetropia.—When a long-sighted eye is at rest, rays are brought to a focus behind the retina. Thus in order to see distant objects a certain amount of accommodation is required to bring the focus forward on to the retina; for near objects the accommodation required is too much for the powers of the eye; this is effected by the use of convex glasses, which bring the focus up to the retina again. Hypermetropia is distinct from presbyopia, which is simply the

loss of power of accommodation due to old age. The shape of the eye itself does not alter with age.

Astigmatism.—In the ordinary or normal eye, the cornea is like a small watch glass, the curvature being the same all the way round. In some eyes it is found that the cornea, or the eye as a whole, is not symmetrical about its axis. That is to say, a vertical section of the eye would show a different curvature to a horizontal section. On looking at a sheet of paper on which vertical and horizontal lines are drawn, such an eye would see the horizontal lines blurred when the vertical lines were distinct, and *vice versâ*. This defect is called astigmatism, and is corrected by the use of cylindrical lenses, lenses which are most curved in the plane in which the vision needs assistance.

Least Distance of Distinct Vision.—A person with normal sight can see objects at a distance when his eyes are at their natural curvature. By the process of accommodation he can focus the eyes to see nearer objects distinctly; but there is a limit to this power of accommodation, and when objects are nearer than a certain distance, he can no longer see them distinctly. This distance, inside which objects become blurred and indistinct, is called the least distance of distinct vision. For persons with normal sight this distance is from 5 to 6 inches. For short-sighted persons it is less, and for long-sighted persons greater.

CHAPTER X

Optical Instruments

Magic Lantern—Photographic Camera—Camera Obscura—Simple Microscope—Compound Microscope—Astronomical Telescope—Eye-pieces—Naval Telescope—Galileo's Telescope—Reflecting Telescopes.

Magic Lantern.—This is an apparatus for throwing on a screen an enlarged image of some object, usually a transparent picture. With the increase of size of the image there will of course be a decrease of intensity of illumination, according to the law of the inverse square (p. 515). If the image is to be bright, it is therefore necessary that a very strong light should fall on the object.

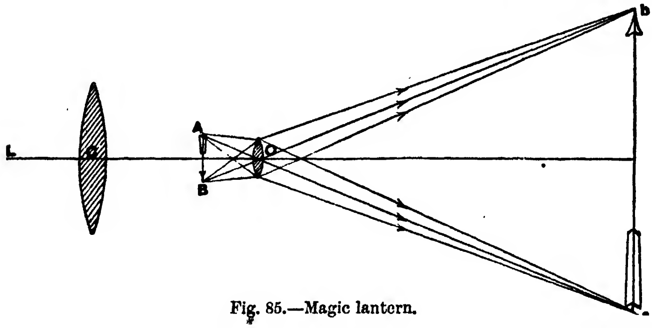


Fig. 85.—Magic lantern.

The source of light may be a powerful oil lamp with reflectors; but a more effective light is given by an oxyhydrogen jet turned on to a cylinder of lime, which is thereby made to glow with an intense white light. Still more powerful is the electric arc-lamp (Electricity, p. 800).

In Fig. 85 is shown the relative position of the essential parts

of the apparatus. Light from the source L falls on a large convex lens C, called the condenser, and is made to converge slightly and fall on the slide AB, which is thus strongly illuminated. Light from each point of the slide passes through the lens O in the nozzle of the lantern and is focussed on the screen, giving an enlarged inverted image of the slide. No light is allowed to reach the screen except by the path indicated.

Pinhole Camera.—This is simply an adaptation of the apparatus shown in Fig. 2, and it can be used when the object whose image is to be formed is strongly illuminated. Each point of the object AB sends its small pencil of rays through the pinhole P, and so an inverted image *ab* is thrown on the

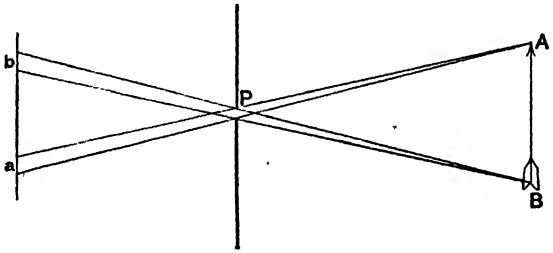


Fig. 86.—Pinhole camera.

screen. Its distinctness will depend on the minuteness of the pinhole, though of course the quantity of light that reaches the screen decreases with the diminution of the size of the pinhole. If the screen is replaced by a sensitive plate, the image thrown on it may be developed and fixed by the use of chemicals.

Ordinary Photographic Camera.—In this a lens or system of lenses is used to form the image on the screen. No light is allowed to reach the screen except through the lens, which is focussed and adjusted so as to throw a clear and undistorted image *ab* of the object AB which is to be photographed (Fig. 87). A sensitive plate or film is then put in place of the screen, the necessary exposure to the light from AB is given, and the chemical effect of the light is developed and fixed on the plate by the use of various washes. The essential part of a good camera is a good lens. A sharp image requires a stop (see

page 560), and the quantity of light falling on the plate is proportional to the area of the stop.

Camera Obscura.—Light from surrounding objects falls on a plane mirror at an angle of 45°, or a totally reflecting prism

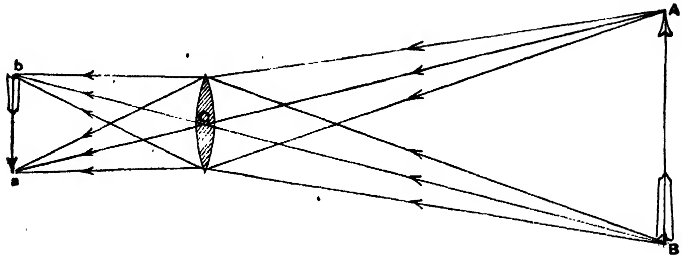


Fig. 87.—Photographic camera.

M, and is thus reflected on to a lens L which forms an image of the object on a screen of white paper on a table. The reflector M is in a roof vertically above the table, and the mirror can be turned about a vertical axis so as to admit light from any

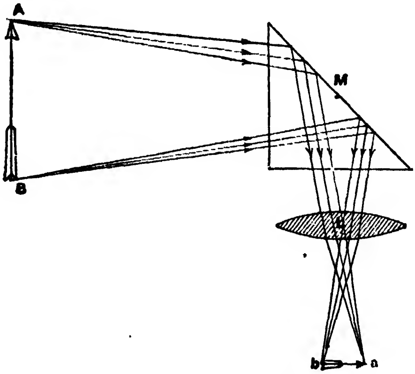


Fig. 88.—Camera obscura.

required point of the compass. The room containing the table on which the image is thrown is shut off from all other light, and hence receives its name 'camera obscura' or dark room.

Simple Microscope.—This consists of an ordinary convex

lens. The course of the rays is shown in Fig. 89. An object PQ viewed through the lens appears to be in the position *pq*. Notice that *pq* and PQ subtend the same angle at the centre of the lens O, since rays passing through the centre undergo no bending (see p. 556). The eye is close up against the lens, so

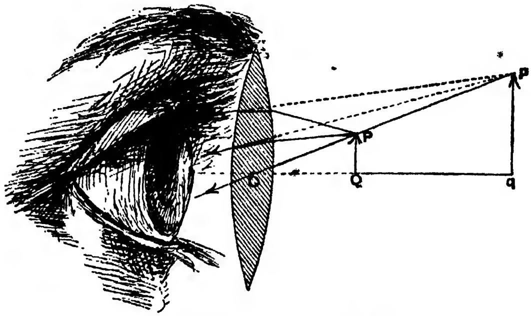


Fig. 89.—Simple microscope

that practically both the object and its image subtend the same angle at the eye, and the apparent size of the object is unaltered. But then the object itself is close to the eye, so close that if the lens were not there *it would be too close to be seen distinctly*, in other words, nearer than the least distance of distinct

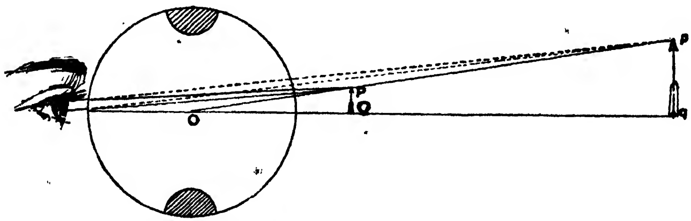


Fig. 90.—Coddington's lens.

vision (p. 570). Therefore the effect of the lens is to shift the apparent position of the object to a distance at which it can be seen clearly, whilst bending the rays so that the apparent size is unaltered. Often the simple microscope consists of a combination of two lenses close together.

Coddington's Lens is a sphere of glass arranged with a

stop, so that only rays passing near the centre of the sphere are allowed through (Fig. 90). The stop is generally made by cutting a groove round the sphere like a belt, and filling the groove with some opaque substance.

STANHOPE'S LENS (Fig. 91) is a cylinder of glass with one end ground into a spherical surface S, and the other end plane, and the length of the cylinder is such that objects placed *on* the plane surface P are in focus when the convex end is turned towards the eye. This gives a convenient way of mounting small objects, and is used especially for small photographs, which are fixed to the plane surface.

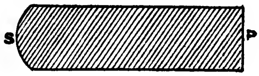


Fig. 91.—Stanhope's lens.

Compound Microscope.—The principle of this is shown in Fig. 92. The small lens O (called the object-glass, and having

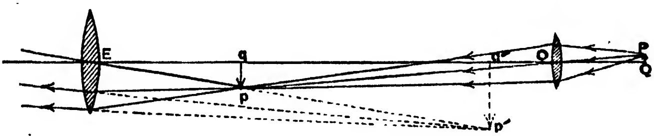


Fig. 92.—Compound microscope.

a short focal length) forms a magnified image *pq* of the object PQ. A second lens E, called the eye-piece, is placed so that *pq* comes near its principal focus, and, as in the simple microscope, shifts the apparent position of *pq* to the least distance of distinct vision $p'q'$.

In good microscopes the object-glass is an achromatic system of lenses (see p. 562), and the eye-piece also consists of two lenses.

Note that the eye receives an inverted image of the object.

$$\text{Magnification} = \frac{p'q'}{PQ} = \frac{p'q'}{pq} \times \frac{pq}{PQ} = \frac{Eq'}{Eq} \times \frac{Oq}{OQ}.$$

Astronomical Telescope.—The arrangement of lenses in this is the same as in the compound microscope. The object glass O (Fig. 93) is large, and since the instrument is used for viewing very far distant objects, the rays that fall on O are parallel, and are made to converge to the principal focus of O (see p. 555). Rays coming from a distant point situated on OQ, the axis of

the telescope produced, are thus made to converge to the point q at the principal focus. Rays coming from a distant point in the direction P are brought to a focus at p. The eye-piece E is placed so that its principal focus is also at q. The rays from P therefore all emerge parallel to pE, and the angle subtended by the object PQ is now pEq instead of POQ or pOq; therefore the apparent size of the object is increased in the ratio of these two angles.

$$\left[\frac{\angle pEq}{\angle pOq}=\frac{\tan pEq}{\tan pOq}\text{ (since the angles are very small)}\right.$$

$$=\frac{pq}{Eq}\times\frac{Oq}{pq}=\frac{Oq}{Eq}=\frac{F}{f},$$

where F and f are the focal lengths of the object-glass and the eye-piece respectively,

$$\left.\therefore \text{ magnification}=\frac{F}{f}.\right]$$

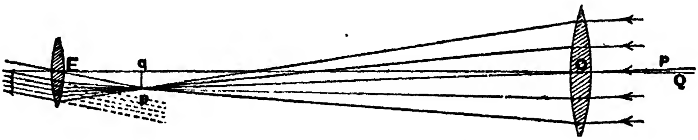


Fig. 93.—Astronomical telescope.

The angle POQ is much exaggerated in the figure for the sake of clearness; so also are the lenses in comparison with the distance between them.

Note that the image is inverted, as in the compound microscope. In looking at heavenly bodies this is no disadvantage as a rule.

Eye-piece.—It is found in practice that a combination of lenses is more satisfactory for an eye-piece than a single lens. The combination may be made so as to diminish and nearly do away with spherical and chromatic aberration. Eye-pieces may be divided into two classes—positive, in which the principal focus is outside of the two lenses; and negative, in which it falls between them. The most common positive eye-piece is RAMSDEN'S EYE-PIECE (Fig. 94). In this the two lenses are of equal focal length,

and the distance between is $\frac{2}{3}$ of that focal length. This eye-piece is used for astronomical purposes, and cross-wires are fixed at the principal focus of the object-glass of the telescope, these are seen through the eye-piece in coincidence with the object under observation, and so can be used for measurements.

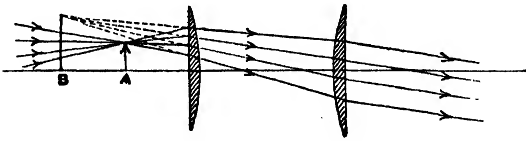


Fig. 94.—Ramsden's eye-piece.

The chief negative eye-piece is HUYGHENS' EYE-PIECE (Fig. 95). In this the field-glass has a focal length three times that of the eye-glass, and the distance between them is twice the focal length of the eye-glass. It was invented by Huyghens to diminish the aberration by making the deviations of the rays at the two lenses equal. It was afterwards found to possess the additional advantage of being achromatic. In Figs. 94 and 95, A is the image formed by the object-glass of the telescope,

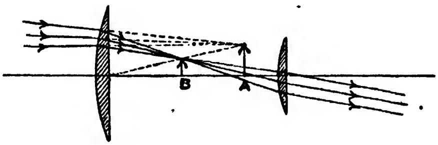


Fig. 95.—Huyghens' eye-piece.

which is converted into the image B by the field-glass of the eye-piece.

ERECTING EYE-PIECES.—For terrestrial objects it is important that the image should be erect, and for this purpose an erecting eye-piece must be fitted to the astronomical telescope. The ordinary erecting eye-piece consists of two lenses of the same focal length placed at any distance apart. Fig. 96 shows how the image is inverted without any alteration of its size. A and B are the centres of the two lenses.

Consider a pencil of rays from a point P of an image PQ situated at the principal focus of the lens A. Since P is at the focus, the rays are parallel when they emerge from A, and consequently after passing through B converge to a point p at the principal focus of B. The principal focus is moved from Q to q; there is no magnification, but the image is upright instead of inverted.

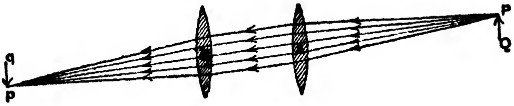


Fig. 96.—Erecting eye-piece.

Naval Telescopes.—The telescopes in use in the navy, such as the Naval Telescope, and the 'Officer of the Watch' telescope, are astronomical telescopes fitted with erecting eye-pieces. Fig. 97 gives a representation of the 'Officer of the Watch' telescope. The focal length of the object-glass is 13 inches, and an inverted image of the distant object is formed at or near the principal focus. The erector reinverts this image into an erect image P′Q′ at

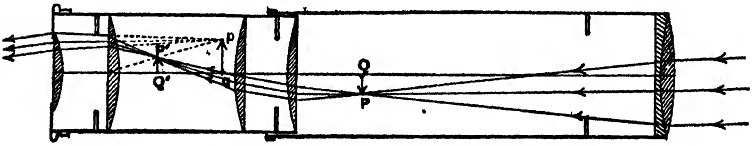


Fig. 97.—'Officer of the Watch' telescope.

the focus of the eye-piece, which itself consists of two lenses. These two lenses are arranged in Ramsden's method as a 'positive' eye-piece, *i.e.* one giving a real image, and having its focus outside the two lenses. The four lenses of the erector and eye-piece are fixed in one tube, and the instrument is focussed by adjusting this tube. There is only one joint to the telescope.

Galileo's Telescope.—This has the advantage of giving an erect image with two lenses only (Fig. 98). The eye-piece is a concave lens, and makes the light diverge. It is placed so as

to receive the light coming from the object-glass O before it reaches its focus. The focus of the eye-piece coincides with the focus of the object-glass, so the rays emerge parallel again. This telescope, invented by Galileo, is shorter than the astronomical telescope, because the distance between the lenses is the difference, not the sum, of their focal lengths.

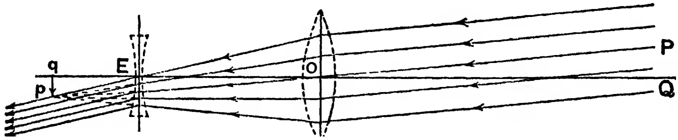


Fig. 98.—Galileo's telescope.

Ordinary opera-glasses consist of two Galileo's telescopes fastened together with their optic axes parallel.

Notice that, as in the astronomical telescope, the magnification is given by a comparison of the angles the light makes with the optic axis after and before passing through the telescope, that is to say, the angles $p\mathrm{E}q$ and POQ, or $p\mathrm{E}q$ and $p\mathrm{O}q$.

$$\left[\frac{p\mathrm{E}q}{p\mathrm{O}q}=\frac{\tan p\mathrm{E}q}{\tan p\mathrm{O}q}=\frac{pq}{\mathrm{E}q}\times\frac{\mathrm{O}q}{pq}=\frac{\mathrm{O}q}{\mathrm{E}q}=\frac{\mathrm{F}}{f},\right.$$

where F and f are the focal lengths of the object-glass and the eye-piece respectively.]

Newton's Reflecting Telescope.—It has been mentioned (p. 561) that Newton was under the impression that dispersion of colour and refraction were inseparable, that therefore a refracting telescope must necessarily exhibit dispersion, and that the more powerful the lenses the more widely separated must the colours be. This we know to be incorrect; but Newton's mistake had its advantages, for it led him to invent his reflecting telescope. All colours are reflected alike, and white light after reflection is white light still. So Newton, instead of collecting the rays by a lens, used a curved mirror or *speculum* of polished metal to bring the light to a focus. Then, in order that the observer should not stand in his own light, Newton placed a

small plane mirror M, making an angle of 45° with the axis of the curved mirror C, to reflect the light at right angles. Newton used, instead of a plane mirror, a total reflection prism M (Fig. 99), in which the loss of light is less. The image *pq* formed by

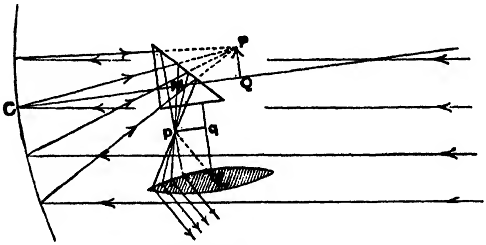


Fig. 99.—Newton's reflecting telescope.

the speculum and reflected by M is then viewed by an eye-piece E, as in the astronomical telescope. The mirror or prism serves to correct spherical aberration in the speculum by shutting off the central rays.

Herschel's Reflecting Telescope.—Herschel's telescope is a

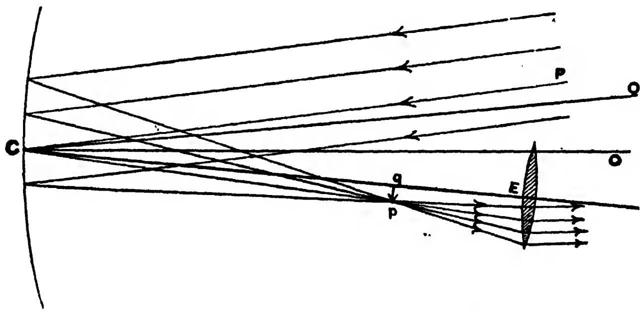


Fig. 100.—Herschel's reflecting telescope.

reflector, like Newton's, but so placed that the axis of the large mirror makes a slight angle with the direction of the incident light which is reflected to a focus on the other side of the axis, and so can pass *direct* to an eye-piece without any light being shut off by the observer himself. In Fig. 100, CQ is the axis of

the tube of the telescope, slightly inclined to CO, which is the axis of the large mirror or speculum. CE is the axis of the eye-piece, equally inclined with CQ to CO. Light incident in the direction QC is brought to a focus at q, and light incident in the direction PC is brought to a focus at p, so that pq is the image of a distant object which subtends the angle PCQ.

Herschel's arrangement is only applicable when mirrors of very large diameter are used. Lord Rosse's great telescope is of this class, the diameter of the speculum being 6 feet, and its focal length 53 feet.

Other reflecting telescopes are GREGORY'S and CASSEGRAIN'S. In these, two curved mirrors are used, arranged in such a way that the observer looks in the direction of the incident light. Gregory described his telescope in a book published in 1663, so that he may be said to be the inventor of the reflecting telescope. Most of the telescopes now used are refractors.

The great telescope at the Lick Observatory in America, with which the fifth satellite of Jupiter was discovered, is a refractor with an object-glass 36 inches in diameter. The Yerkes telescope of Chicago University has an object-glass 40 inches in diameter. These large lenses have the disadvantage of being far more costly than reflectors.

CHAPTER XI

Interference and Diffraction

Colours of Thin Plates—Newton's Rings—His explanation of them—Explanation according to Wave Theory—Light from two Different Sources—Young's Interference Experiment—Fresnel's Mirrors—Diffraction—Difficulty of explaining Rectilinear Propagation of Light—Shadow thrown by a Straight Edge—Narrow Obstacle—Narrow Aperture—Diffraction Gratings—Method of Measuring Wave Length—Colour and Wave Length—Summary of Results.

Interference Phenomena.—We now come to a group of phenomena more interesting than any we have yet considered, because more closely connected with the origin and basis of the wave theory. The subject of the interference of waves has been treated of in Wave Motion, and that subject should be studied in order that the explanation of the appearances hereafter described may be understood.

Colours of Thin Plates.—We have all seen the beautiful colours in the film of a soap-bubble. These colours do not appear in an ordinary solution of soap standing in a vessel; but directly the solution is shaken so as to form bubbles, the colours make their appearance. A similar appearance may be noticed on the surface of water which has been contaminated with a little tar, or on which a few drops of turpentine have been poured. A thin film of turpentine spreads over the water, and light reflected from the surface is broken up into colours. Any transparent substance when split into very thin plates will show these colours; talc and Iceland spar, crystals with very perfect

cleavage, are instances; air in thin films is another. When we see this colouring on the surface of glass we are often right in assuming it to be due to a thin film of dirt, *i.e.* matter in the wrong place. A thin plate of any transparent medium is all that is necessary for the colouring. Take two pieces of smooth and perfectly clean glass, and hold them together between the finger and thumb. Coloured rings will be seen in the region of the compression, and these rings widen out if the pieces of glass are pressed together more tightly. The colouring then is evidently due to and dependent on the thinness of the transparent film.

Newton's Rings.—Boyle, and after him Hooke, in the seventeenth century, made many observations of these appearances, and Hooke in particular went some way towards their explanation as now accepted. It was left for Newton to make accurate measurements connecting the thickness of the film with the colour it shows.

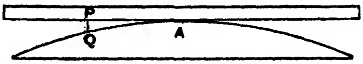


Fig. 101.—Formation of Newton's rings.

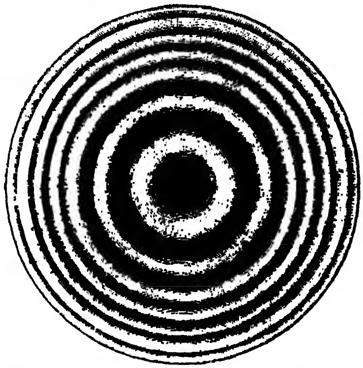


Fig. 102.—Newton's rings (monochromatic).

Newton took a plano-convex lens, the curvature of the convex face being very slight, and placed on it a flat piece of glass, which touched the convex face at the point A (Fig. 101). He thus obtained a film of air between the flat glass and the lens, with its thickness increasing with the distance from the central point A, and the same for all points at the same distance from A. On looking at the film he saw a series of coloured rings, all with their centre at A, and by using light of one colour only he obtained a series of alternate bright and dark rings (Fig. 102). For blue light the diameters of the rings were less than for red light, and the rings contracted as the light was gradually changed

through the spectrum from red to blue. With white light the different colours, having rings of different diameters, were separated, and a rainbow effect resulted, until at some distance from the centre the different coloured rings overlapped, forming white light again. [The thickness of the film at any point P (Fig. 101) can be obtained from the distance AP and the radius R of the convex face. The latter can be obtained by finding the focal length of the lens (p. 558). Then when P is at a small distance from A, we have approximately, by Euc. III. 36, $AP^2 = 2R \times PQ$.]

Newton's Explanation.—Newton's theory was that his light-corpuscles were subject to fits of alternate easy reflection and easy transmission, and that the bright rings resulted from light-particles reaching the further surface of the film in a state of easy reflection, and so coming back, while the dark rings were caused by the particles being in a state of easy transmission, and so passing on. If the light-particles be assumed to have polarity, that is, to be different back from front, and to be rotating so as to present their back and front alternately, Newton's explanation seems reasonable and ingenious. But it assumes that the separating action takes place at the further surface only, and it can be shown experimentally that such is not the case.

Explanation of Newton's Rings on the Wave Theory.—The wave theory explains the rings by referring them to interference (see WAVE MOTION, p. 447). Some of the light is reflected at the first surface of the film, while some passes on and is reflected at the second surface, so that streams of light from two different sources reach the eye simultaneously. Now if the film be of such a thickness that the two streams differ in phase by a wave length or some multiple of a wave length, the two streams will help one another and a bright ring will be seen. But if the streams differ in phase by a half wave length or some odd multiple of it, the streams will counteract each other and darkness will be the result. The rings that are seen by transmitted light are explained as being due to the interference of light which has passed directly through the film with light which has undergone two internal reflections within the film.

Geometrical Explanation of Newton's Rings.—AB (Fig. 103) is a wave-front advancing through glass upon a film of air. If the incidence is perpendicular it is plain that rays which pass into the air and are reflected at the further surface will be a distance $2t$ behind rays which are reflected at the first surface, t being the thickness of the film of air. But if the incidence be oblique, the wave-front in the air film will be ab, and ray No. 2 will travel from A to a while ray No. 1 is travelling from B to b. The total retardation of the second ray will therefore be due to a thickness of air [$ac + a'c = 2ac$ or $2t \cos acb$].[1] The retardation diminishes as the obliquity of incidence increases, and therefore slanting the direction of the light produces the same effect as making the air film thinner, viz. that of widening the rings. Hence the rings increase on increasing the angle of incidence, and their diameters are proportional to the secant of the angle of incidence in air. This result corresponds with the observed phenomena, of which Newton could give no explanation. The wave theory being admitted, it is evident that Newton's rings supply a method for finding the wave length of light.

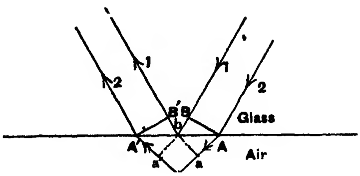


Fig. 103.
Geometrical explanation of Newton's rings

Light from two Different Sources.—In order that two streams of light should neutralise each other, it is necessary that they should agree in their times of starting, or differ by a constant quantity. In the case of light from two flames, or from different parts of the same flame, the times of starting of the waves are continually changing in an irregular manner, so that nothing but the average effect can be observed. In order that interference phenomena may be studied, we must arrange that our two streams of light come from the same source, but pursue slightly different paths.

[1] To this should be added a half-wave-length, the difference in phase caused by the different character of the two reflections. For the same reason, the central spot (Fig. 102) is dark, not bright.

Young's Interference Experiment.—Young tried unsuccessfully to obtain interference effects from sunlight admitted into a darkened room through two small apertures. The two streams of light so obtained have no regular connection with each other, and, though doubtless interference takes place, it must change with such rapidity and irregularity as to be unobservable. If,

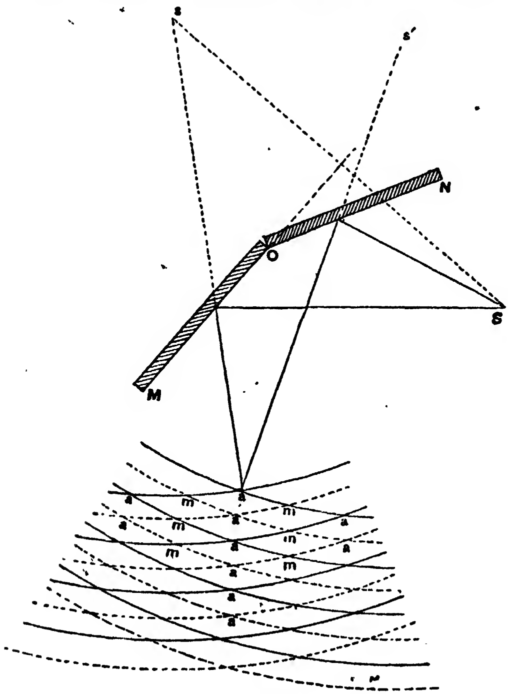


Fig. 104.—Fresnel's interference mirrors.

however, one small aperture be used, and the stream of sunlight from it be intercepted by an opaque screen in which two small holes are made, the two divisions of the stream thus obtained have a regular connection with each other and interfere. This phenomenon was first observed by Grimaldi in the seventeenth century, and repeated by Young and Fresnel, who worked out the complete mathematical explanation of it by the wave theory.

Fresnel's Mirrors and Biprism. — Fresnel invented two beautiful and ingenious methods of obtaining two streams of light differing slightly in phase. First he took two plane mirrors, ON, OM (Fig. 104), inclined at a very obtuse angle. Placing these in a darkened room, into which a beam of sunlight was brought to a focus S, he obtained two virtual images of S, viz. *s* and *s′*, in the two mirrors. The two streams of light

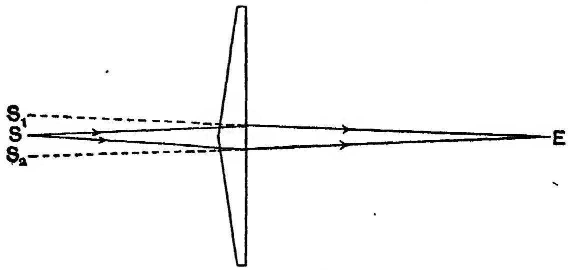


Fig. 105*a*.—Fresnel's biprism.

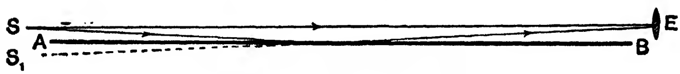


Fig. 105*β*.—Lloyd's single mirror.

travel slightly different paths, one set of waves diverging from *s* and the other from *s′*, as shown in the figure. The plain and dotted circles in the figure show the 'crests' and 'hollows' of the waves. Where crest coincides with crest and hollow with hollow, as at the points *a a* . . . , there will be a bright band, but where crests meet hollows, as at *m m* . . . , they neutralise each other and a dark band results. Fresnel also obtained a similar result by using a biprism, two prisms of small angle back to back, usually made as a single prism of wide angle (Fig. 105*a*), by which light from a single small source S was deviated into two streams of slightly different path. The easiest way of obtaining interference bands, however, is with Lloyd's single mirror. This is a strip of plate-glass AB about 18 inches long and $1\frac{1}{2}$ inches wide, mounted with its surface vertical. An illuminated vertical slit is placed a little way from one end, and very near the surface. An eye near the other end can see both the

slit S and its image S_1, and if these are near together, interference bands will be easily seen if an eye-piece is used (Fig. 105β).

The interference phenomena in these cases are exactly similar to that illustrated in WAVE MOTION, p. 446, where the waves that interfere are ripples on the surface of mercury.

Diffraction.—Difficulty of explaining Rectilinear Propagation.—The greatest difficulty encountered by the exponents of the wave theory of light was the fact that light travelled in straight lines. Why should opaque objects throw such sharply defined shadows? Why should the sun's light breaking through clouds or entering a room through a chink in a shutter be so obviously straight in its course? Waves in air and water were

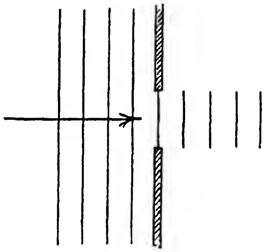


Fig. 106.—Wide aperture.

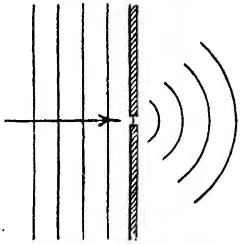


Fig. 107.—Narrow aperture.

known to turn corners. If light, like sound, were really wave-motion, why should it differ from sound by its inability to turn a corner?

In answer to these questions, it may be stated shortly that—

(i) Light does turn corners slightly.

(ii) Sound shadows are known to exist.

It has been shown in WAVE MOTION (p. 449) that the sharpness of 'shadows' is dependent on the length of the waves. The shorter the waves the more sharply defined the shadows. Now the average wave length of light is $\frac{1}{50000}$ of an inch, while the wave lengths of the sounds of the human voice vary from 2 to 12 feet.

When a wave-front passes through an aperture large in comparison with the wave length, the effect is more or less that

shown in Fig. 106; whereas if the aperture be at all comparable with the wave length, the disturbance is propagated in all directions (Fig. 107). So when sound passes through an aperture of a few feet in diameter, it diverges in all directions; but when it passes through an aperture of several hundred feet in width, such as a street or a mountain gorge, it travels approximately in straight lines like light. On the other hand, if light be made to pass through a slit whose width is comparable with $\frac{1}{50000}$ of an inch, we see it diffracted in all directions.

Shadow thrown by a Straight Edge.—If light from a luminous point O (Fig. 108), such as the image of the sun produced by a lens of short focus, or from a narrow slit, be allowed to fall on a white screen PQ, and the edge A of an opaque card AB

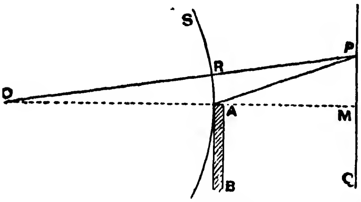


Fig. 108.—Diffraction at straight edge.

Fig. 109.—Diffraction fringes.

be placed parallel to the slit, so as to throw a shadow on the screen, it will be found that the edge of the shadow is not absolutely sharp at M, as would be the case if light travelled in straight lines, but that the light fades away rapidly but gradually, and that complete darkness is reached a little below M. Above M the screen is not uniformly bright, but a series of fringes are seen parallel to the edge fading away into uniform brightness a little above M (Fig. 109).

Young tried to account for these fringes as the result of interference of direct light with light reflected at a grazing incidence by the edge of the card. Fresnel showed that they are explained naturally as resulting from the interference of secondary waves, part of which have been cut off by the opaque screen. (WAVE MOTION, p. 439). The observed position of the fringes

agrees exactly with that calculated on the assumption of the wave theory.

Narrow Obstacle.—If, instead of a screen with a straight edge, a narrow wire be put in the path of the light coming from the slit, the diffraction fringes produced by the two edges of the wire may be made to overlap, and it is possible so to adjust the distances that a bright line is seen in the centre of what *should be* the shadow of the wire if light travelled in straight lines. Or if the source of light be a luminous point, and a small circular disc be put in the path of the light, the fringes are circular, and it is possible to adjust the position of the disc so that the centre of the *geometrical shadow* is a bright point. With a disc of the size of a sovereign this can be done, brilliant coloured fringes being produced round the shadow of the coin.

Narrow Aperture.—If a narrow slit be cut in a card and placed close to a candle, and if the light from the slit be viewed through another slit held close to the eye, diffraction fringes may be observed. And if a small circular aperture, such as a pinhole in a sheet of metal, be placed near the source of light and viewed through a pocket lens, most brilliant circular fringes are seen, opening out and changing colours as the distance of the eye from the pinhole is changed. Theoretically it should be possible so to adjust the distances that the centre of the luminous patch should be dark. This strange result can be and has actually been obtained.

Diffraction Gratings.—Method of Measuring the Wave Length of Light.—A diffraction grating is made by ruling with a fine diamond point a number of parallel lines very close together on a plate of glass. The lines cut off the light, while the spaces between allow it to pass freely. Rowland, the unrivalled maker of gratings, considered that 15,000 lines to the inch give the best results; they have been made with three times as many. When light from a narrow slit is viewed through such a grating, a central image of the slit will be seen, and on either side of it a series of coloured images, the colours being more spread out the further they are from the central image. A telescope should

be focussed on the slit, and the spectral images formed by the grating will then be visible through the telescope. Fig. 110 shows the light coming through the grating MB, and brought to a focus by the lens.

If the telescope be made to move on a graduated circle at whose centre is the grating, the angular distance of the first spectral image of the slit from the central image can be measured. If the distance apart of the lines of the grating be known it will then be possible to calculate the wave length of light of any particular colour. To explain this we must go back to the wave theory. When two streams of light arrive at the same

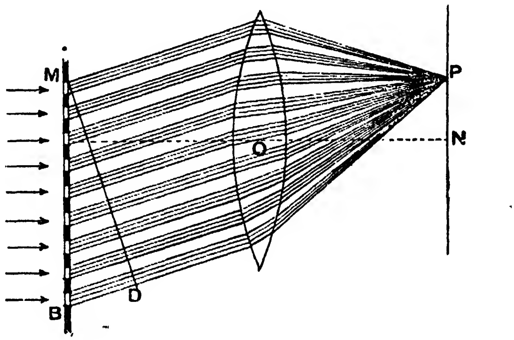


Fig. 110.—Diffraction gratings.

point in opposite phases, *i.e.* when the crests of one set of waves arrive at the same time as the troughs of the other set, the result will be darkness. This is the case when light travels from one point to another by two different paths differing in length by half a wave or an odd multiple of half a wave. But when the paths differ in length by a whole wave, then the two crests arrive simultaneously and reinforce each other, the result being increased brightness.

Now if B_1A_1, B_2A_2 etc. (Fig. 111) be the apertures, then it is obvious that there will be a central image at M, while the next bright spot will be at P, where the distances of successive apertures from P differ by one wave length. The apertures, of course,

are enormously exaggerated in the figure. In the figure then B_2C represents a wave length of light. The angle B_1B_2C has been measured (say θ), and we know the distance B_1B_2. Therefore we have by trigonometry $B_2C = B_1B_2 \cos \theta$.

The values of the wave lengths thus obtained correspond exactly with those given by Fresnel's biprism and double mirror, where the phenomenon is one of simple interference.

If light of one colour only be used, the successive images are of that colour and of the same width. But if white light be used, the grating separates the colours like a prism, thus proving that different colours correspond to different wave lengths. A grating may be used instead of a prism in a spectroscope, and

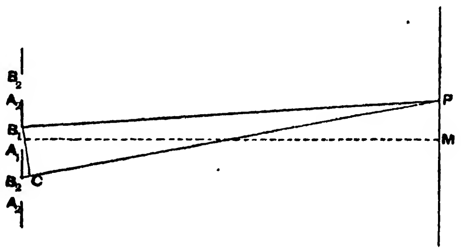


Fig. 111.—Interference—Diffraction gratings.

it has the advantage of giving a pure spectrum, *i.e.* one in which the colours belonging to the same spectrum do not overlap.

Diffraction gratings can be used to reflect the light instead of transmitting it, and similar effects of colour-bands due to interference are seen. The plumage of birds owes much of its beautiful colouring to diffraction, the fine divisions of the feathers acting in the same way as the fine lines of a grating; the changing colours of a cock pheasant's neck are a good example. Metal buttons, ruled with very fine lines, and giving beautiful diffraction colours by reflection, used to be worn as ornaments.

Colour and Wave Length.—We can now recapitulate the facts we have learnt which bear on the subject of colour.

(i) *Different colours travel with different velocities.*—A narrow

beam of sunlight passing through a prism of glass is widened out into a band of colours, ranging from the least refrangible red to the most refrangible violet. Assuming that light of all colours travels with the same velocity in a vacuum, the wave-theory would show that in glass and other refracting substances the red rays are retarded less that the violet.[1]

(ii) *The proportion of the retardation* of rays of different colours varies very much in different substances. This is further discussed on p. 601.

(iii) *Different wave lengths cause different colour sensations.* This has been shown by the coloured bands produced by diffraction, by grating spectra, by Newton's rings, and by Fresnel's interference experiments. The measurements obtained from these show that the wave length of light ranges roughly from $\frac{1}{30000}$ in. ($\cdot$00082 mm.) in the red to $\frac{1}{60000}$ in. ($\cdot$00043 mm.) in the violet, intermediate wave lengths producing to the eye the sensations of orange, yellow, green, and blue.

We infer from the above facts that light-waves of all lengths travel at the same rate in a vacuum, by which we mean a region destitute of ordinary 'matter,' that the presence of solid, liquid, or gaseous matter has the effect of retarding them, and that in general the shorter waves are more retarded than the longer. In the present condition of science, no further general laws can be stated, for every substance appears to differ from every other substance in its effects on light-waves.

[1] A recent theory regards white light as a succession of more or less irregular pulses, and considers that a prism or a grating sifts out these pulses into groups of regular wave-trains; in other words, that the prism or the grating actually creates the colour by impressing regularity where little or none existed before. (See *Wood's Physical Optics,* Chap. xxi., in which recent work is described and discussed.)

CHAPTER XII

The Spectroscope

Principle of the Spectroscope—Mode of obtaining a Pure Spectrum—Table Spectroscope—Direct Vision Spectroscope—Spectra of Incandescent Solids and Vapours—Fraunhofer's Lines—Rays beyond the Visible Spectrum.

The spectroscope is in the first instance an instrument for analysing the colours in any kind of light. The simplest form of such an instrument is furnished by Newton's prism experiment (p. 542), in which a narrow beam of sunlight is analysed by a prism and thrown on a screen. This is only possible with a very strong light, and a more elaborate arrangement is necessary to view the colours given out by different kinds of matter in a state of combustion or incandescence (*i.e.* burning or glowing). But the means by which the colours are separated are always simple, and consist either of a prism or of a diffraction grating. When a prism of glass is used, the dispersion of the colours seems to depend on their *different velocities in glass*; when a grating is used, the dispersion is due more directly to their *different wave lengths.*

Pure Spectrum.—However narrow the slit we allow the sunlight to pass through, the light received on a screen comes from each portion of the sun's surface, and a band of breadth ss' (Fig. 112) is formed on the screen. Now if a prism be interposed, the red rays are refracted, and come into the position rr'. Each colour is refracted in the same way, and the bands of consecutive colours overlap, in other words the spectrum is not

pure. By putting a convex lens in front of the slit we can form an image of the slit on the screen instead of a broad band of light (Fig. 113). Now if the prism be interposed in the position of minimum deviation, the screen receives an image of the slit in each colour, and (*if the slit be narrow*) there is very little overlapping. The minimum deviation for red rays is not the same as for violet, so the prism is placed to give minimum deviation for an intermediate colour, it being remembered that

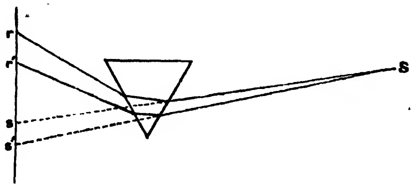


Fig. 112.—Spectrum projected on a screen.

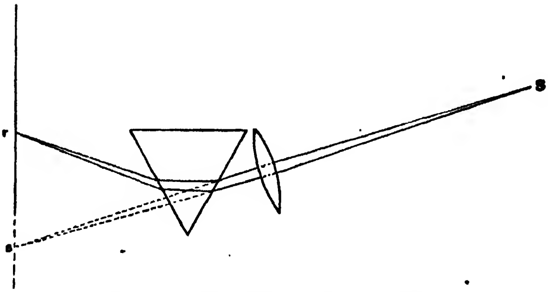


Fig. 113.—How to obtain a pure spectrum.

in the minimum position the deviation is stationary, a slight turn of the prism producing no change (see p. 540). But without parallel light the spectrum cannot be absolutely pure.

Table-Spectroscope.—A simple plan of this instrument is shown in Fig. 114. Light from the flame which is being examined passes through a slit S and falls on a collimator, that is to say, a lens or lenses arranged to give a parallel pencil of rays. The rays that fall on the prism P are parallel, and therefore, after refraction at the two surfaces of the prism,

the rays of each colour emerge parallel, *i.e.* the red rays are all parallel to each other, so are the yellow, green, violet, etc. On falling on the achromatic object-glass O of another telescope, a small bright image of the slit is formed at its focus in each colour; this forms at F a pure spectrum, but small. The eye-piece E gives the observer an enlarged image of it. Often a series of prisms is used instead of the single prism. The telescope OE can be turned about the centre P by the milled-headed screw B, and the angle through which it is turned can be read by the vernier V. For purposes of measurement, another telescope A

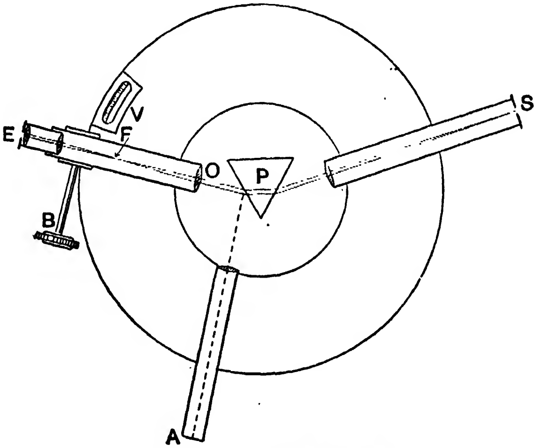


Fig. 114.—Plan of spectroscope.

throws light from a scale illuminated by a lamp on the second surface of the prism. This is conveyed by reflection to the eye, and so gives a means of measuring the position of any particular colour or line in the spectrum.

A diffraction grating may be used instead of the prism.

Direct Vision Spectroscope.—This is an adaptation of the spectroscope as a pocket instrument. By using three prisms, one of flint-glass and the other two of crown-glass, with their edges the opposite way to the flint-glass prism, the deviation of the light is got rid of, while the colours are separated, owing to

the different dispersive powers of crown- and flint-glass. Fig. 115 shows the arrangement of the prisms. S, a slit admitting the light, can be adjusted in width; L is a convex lens converting the light from the slit into a parallel beam, which falls on the three prisms, of which 1 and 3 are crown-glass, while 2 is flint-glass. The dispersed light passes on to the eye placed at E. The instrument has two tubes, so that the lens can be focussed on the slit.

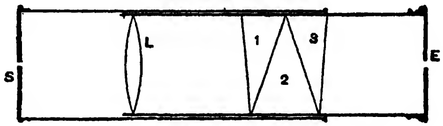


Fig. 115.—Direct vision spectroscope.

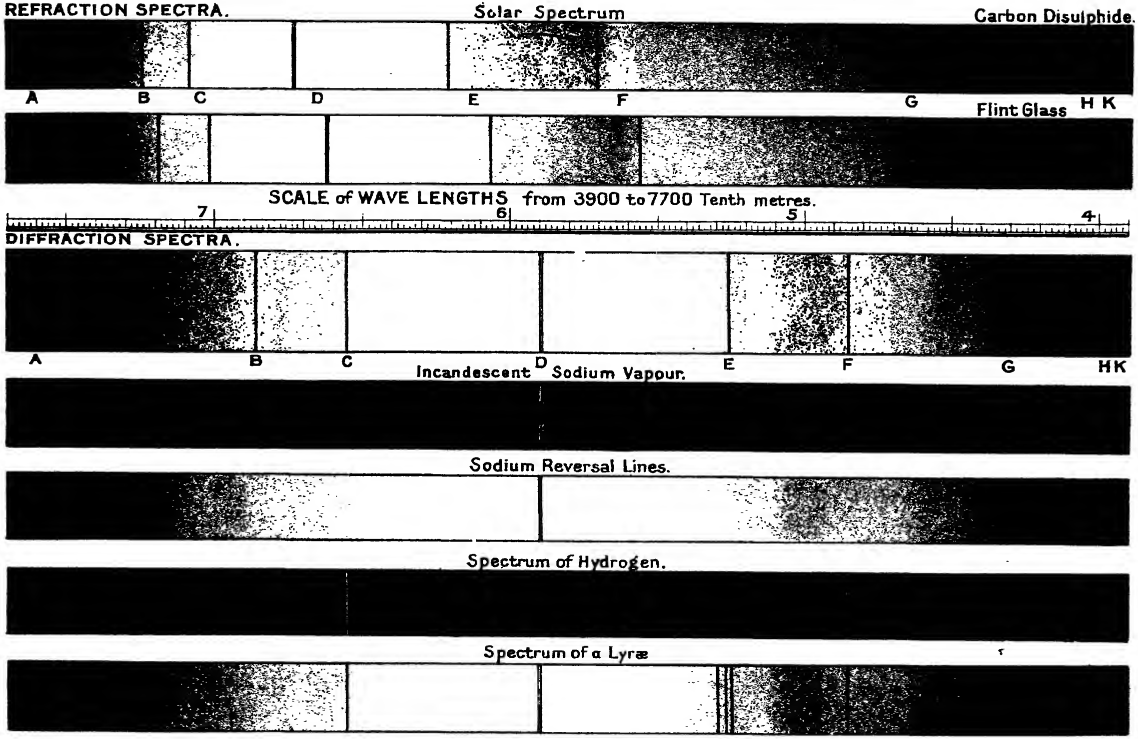
Spectra given by Various Substances.—If we examine with the spectroscope the light given by different flames and heated bodies, we find striking differences in their spectra. A glowing solid gives *a continuous spectrum.* Examine the light of an incandescent electric lamp with the spectroscope. When the carbon filament is white hot we see a continuous band of colour, ranging from red to violet; if the electric current is turned off the band of colour dwindles, the violet end disappearing first and the red being last to go; but there are no gaps in the band. The pulses caused by the hot carbon are capable of being resolved into wave-trains of all lengths within a range which widens with the temperature. Wien has formulated a law for the change of the spectrum of a glowing solid with the temperature.

A glowing gas or vapour gives a spectrum of quite a different character. Instead of a broad band of colour, we find a few bright lines of different colours in their proper positions in the spectrum, the space between the lines being quite dark. From this we infer that the light waves produced by an incandescent vapour are capable of being resolved into *certain particular lengths only.* As an instance we will take sodium light.

Sodium Light.—If a little salt (chloride of sodium) be put on the wick of a spirit-lamp, the flame, almost colourless before, becomes a very pure yellow. The flame of a Bunsen burner is

colourless; but if a platinum wire be dipped in common salt or carbonate of soda and held in the flame, the same pure yellow colour is produced. All sodium salts give this colour to the flame. If the flame thus produced be examined with the spectroscope, the light is found to be lacking in red, green, blue and violet, and the image of the slit, instead of being a continuous band, consists of a narrow yellow line, or rather *two yellow lines very close together*. The wave lengths corresponding to these two lines are ·0005895 mm. and ·0005889 mm. We may suppose the atoms of sodium vapour to be in a violent state of agitation and able to produce vibrations in the ether, and that the period of these vibrations is always the same, producing waves of the above lengths. The coloured plate given on the opposite page shows the spectra of incandescent sodium vapour and hydrogen. These are seen to consist of bright lines of definite wave lengths, which seems to show that each kind of atom has its own characteristic vibration.

Fraunhofer's Lines.—If sunlight be examined with a good spectroscope, it is found that a large number of dark lines occur in various places. The coloured picture of the solar spectrum shows a few of these lines. Diffraction gratings are now made by ruling lines on speculum metal, with a diamond point, as many as 19,000 lines being crowded into one inch. With such a grating the spectrum has been dispersed to more than 100 yards in length, and the number of Fraunhofer's lines observed is practically without number. Some idea of the multitude of these lines is given by Fig. 116, which represents the portion of the solar spectrum between the lines D (wave lengths 5895 and 5889) and E (wave length 5269), in which interval there are 511 lines. These are now printed by photography, and can be examined with a microscope. Fraunhofer was the first to notice that a number of these lines coincided in position with bright lines noticed in certain artificial flames. For instance, the twin line marked D in the solar spectrum coincides exactly with the yellow line found in sodium light. The cause of these dark lines was explained by Professor



REFRACTION SPECTRA.
Solar Spectrum
Carbon Disulphide.
A
B
C
D
E
F
G
H K
Flint Glass
SCALE of WAVE LENGTHS from 3900 to 7700 Tenth metres.
7
6
5
4
DIFFRACTION SPECTRA.
A
B
C
D
E
F
G
HK
Incandescent Sodium Vapour.
Sodium Reversal Lines.
Spectrum of Hydrogen.
Spectrum of α Lyræ

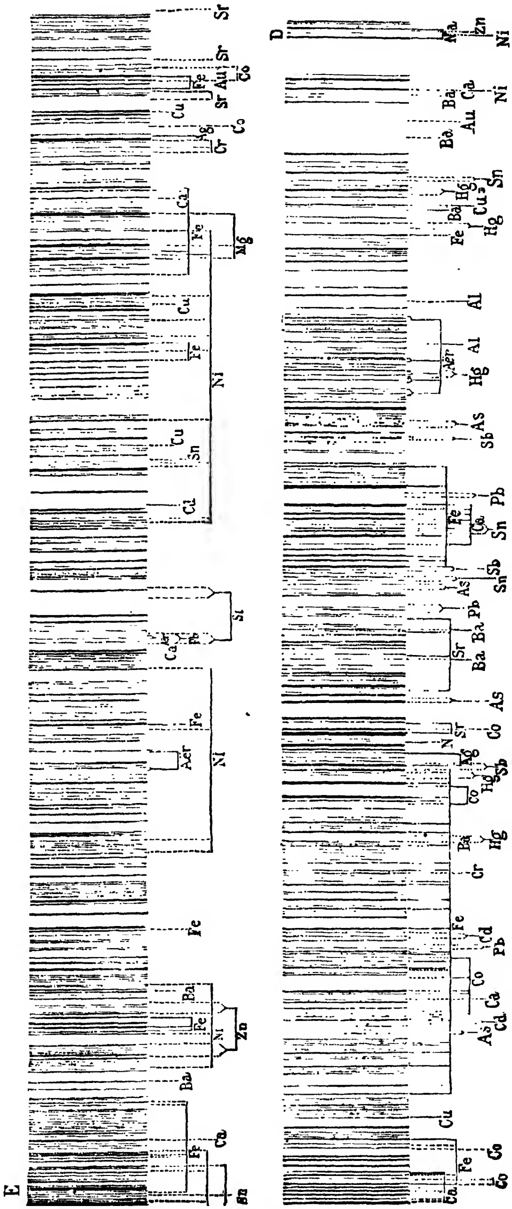


Fig. 116.—Portion of spectrum between D and E.

Stokes in 1852. We will describe an experiment which will help to make it clear. Let light giving a continuous spectrum, such as the light given by the electric arc lamp, be made to pass through a flame coloured yellow with sodium light by putting common salt or sodium carbonate in it, and then be examined by the spectroscope. There will then appear a dark line, or two narrow dark lines, in the yellow where the sodium light ought to be. The particles of sodium in the flame, while capable of giving rise to vibrations of certain periods, are also capable of taking up and absorbing such vibrations coming from another source. It has been observed (SOUND, p. 478) that a violin A string may be set in vibration by simply holding an A tuning-fork near it. The arc lamp is at a higher temperature than the sodium flame; among the vibrations of all periods into which its energy can be resolved, the sodium particles take up and absorb the vibrations of certain periods, leaving the corresponding part of the spectrum darker than the other parts which have not lost the energy of their vibrations.

Importance of the Dark Lines in Solar and Stellar Physics.—The dark lines in the solar spectrum can now be accounted for. The light coming from the main body of the sun has to pass through an outer envelope of various materials in a state of vapour. Supposing sodium particles to be present in this vapour, they would select and absorb the waves of their own period, and so cause those waves to come to us with their intensity diminished by comparison with their neighbours; in other words, the place in the spectrum occupied by sodium light would appear dark by comparison. The dark D line then (Plate) proves the existence of sodium in the vapour surrounding the sun. In the same way the other dark lines correspond to other elements which we thus know to be present in the sun. In Fig. 116 the elements corresponding to the different lines are indicated by their chemical symbols. Similar dark lines are found in the spectra of the fixed stars. Thus we learn from the spectroscope that the sun and stars contain many of the elements which compose our own earth.

This study is receiving daily additions, yet even now it is marvellously fruitful. Professors Lockyer and Huggins have shown that the bright lines given out by gases, and consequently the dark absorption lines corresponding to them, differ completely in gases at different pressures. These observers announce that they have observed the lines H and K in the violet (known to belong to calcium and seen alone of the calcium lines in the solar spectrum) alone in this gas when much attenuated. Here is probably the future of a quantitative analysis of the stars.

Also the position of known lines in the spectra of stars gives a clue to the motion of the vapours which show those lines. Just as a locomotive's whistle has a sharp note of shorter wave length when it is approaching, which becomes flatter after the train has passed, so the shifting of a line towards the violet end implies approach and, towards the red, removal of the vapour.

Irrational Dispersion.—The diffraction spectra seen with a grating show a greater proportion of red and a smaller proportion of violet than the refraction spectra seen with a prism. The Fraunhofer's lines form landmarks in the spectrum by which the dispersion of the different parts may be accurately observed.

With a grating spectrum the dispersion of the lines varies as the difference of their wave lengths; this spectrum is accordingly called a *Normal Spectrum.* In the plate opposite p. 598 the scale above the normal spectrum gives the wave lengths corresponding to the different lines, a few of which only are drawn. With a prism the proportion in which the different colours are separated depends on the material of the prism and is different for different substances. This is called *Irrational Dispersion*, and is shown by the two top spectra opposite p. 598. The lines A to D in the red are closer together in both refraction spectra, and the lines F to H in the violet more spread out than in the diffraction spectrum.

Anomalous Dispersion.—Infusions of some dye-stuffs, such as indigo, fuchsine, etc., give spectra, which are quite anomalous, for the yellow is most refracted and the violet least. This effect

is only observed in substances which have a surface colour; it is ascribed to the total reflection of light of certain wave lengths by the suspended particles and subsequent internal reflection at the surface of the liquid. By such a means the colours would be reversed, as in the secondary rainbow.

Ultra Red and ultra Violet Rays.—The name light is given only to those waves which act on the sight. These range in length from $\frac{1}{30000}$ inch to $\frac{1}{60000}$ inch roughly. But we know of the existence of waves beyond these limits by other effects produced by them. We know that the light of the sun brings with it heat, that the radiant heat so brought obeys the laws

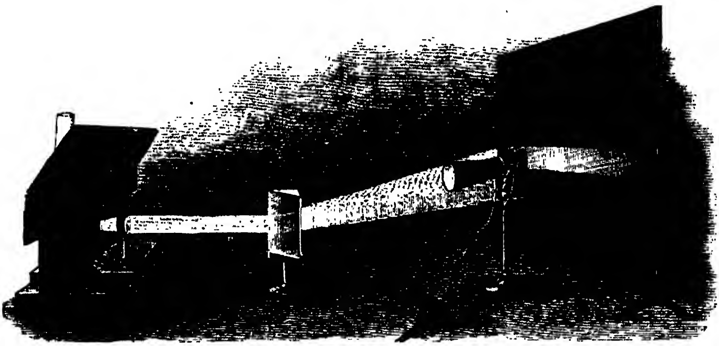


Fig. 117.—Picture of thermopile in spectrum.

of reflection and refraction of light, and that it can be brought to a focus by a lens. Let us separate the rays by a prism, and examine their heating effects separately by a thermopile or sensitive thermometer placed in different parts of the spectrum.

We can thus determine which rays bring most heat, and we find that the violet rays have no heating effect. In Fig. 118 the heating-power of the different parts of the spectrum is shown by the curve, the height of the curve above the line AE at any point, *e.g.* DC, giving the relative heating effect at that point. If we go beyond the red end of the spectrum, as at B, we find a powerful heating effect though no light is to be seen. Waves of greater length than the red exist which have no effect

on the vision, but which convey heat. These are spoken of as the invisible heat-rays, or the ultra red rays.

The violet rays have little or no heating effect. On the other hand, they have a powerful chemical action in which the

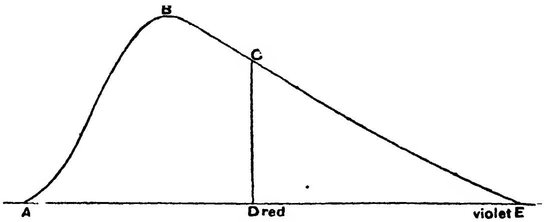


Fig. 118.—Curve showing heating effect of different parts of the spectrum.

red and yellow rays are wanting. And beyond the violet we find that rays exist which act on a photographic plate, but which are invisible to the eye.

The invisible spectrum at the violet end has been mapped out by photography, just as that at the red end has been mapped out with the aid of the bolometer (see p. 395). Dark lines similar to the Fraunhofer lines are found there also, and letters extending to R have been assigned to the principal ones.

Photographers use a yellow or red lamp to give them light for developing, because the longer waves have little or no effect on the salts which they use.

CHAPTER XIII

Colour

Colour in Natural Objects—Transmitted and Reflected Light—Complementary Colours—Mixture of Pigments · Mixture of Colours—Newton's Disc—Maxwell's Discs—Duration of Impressions on the Retina—Phosphorescence—Fluorescence.

Colour in Natural Objects.—When light passes through a red glass is all the light changed to red? This question can be answered by holding a red glass in front of a slit through which white light is falling on a prism. We find that the yellow, green, blue, and violet rays are almost entirely cut off, and that the red rays are unaffected. This tells us that coloured glasses are coloured because they only allow light of their own favourite colour to pass, absorbing all the rest. Now take a strip of coloured paper, say red, and hold it in the different parts of the spectrum. It appears of its natural colour in the red portion, but in the other portions it seems black. This tells us that an object appears red because it absorbs other colours, reflecting or scattering red only.

Transmitted and Reflected Light.—Smoke consisting of very fine particles, such as that from a cigarette end, appears of different colours according to the position of the light. Against a dark background it appears blue, but against the sky it appears of a reddish brown. The shadow cast by such smoke is of a distinctly brown colour. Again, if a little soap be dissolved in a tumbler of water so as to make it slightly turbid, the same difference in the colours of reflected and transmitted light is seen

as in the case of the smoke. In each case the fine particles scatter the light of smaller wave length, allowing the longer waves to pass through. This is also supposed to be the reason why the sky is blue. The shorter waves of blue are scattered more than the longer waves of other colours. At sunset and sunrise the sun appears red. When the sun is near the horizon its rays have to travel through a greater thickness of atmosphere to reach us than when it is over our heads. The longer waves (red and yellow) suffer less scattering and absorption than the shorter waves. Even at noon the sun seems yellow at times rather than white, owing to the scattering of some of the blue light by the atmosphere.

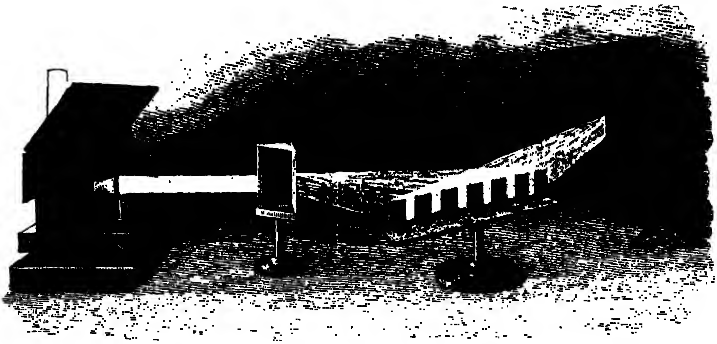


Fig. 119.—Colours of spectrum recombined.

Complementary Colours.—If the colours of the solar spectrum be recombined in the proper proportions we get white light again. This can be done by the arrangement of mirrors shown in Fig. 119, each mirror having a different colour of the spectrum to reflect and all the mirrors being arranged to throw their light on the same spot of the screen. The spot will appear white. If one of the mirrors, say that placed in the green light, be turned away a little, the spot on which all the other colours fall will now appear not white but red. If we replace the green and remove the yellow, the remaining colours make a blue spot. We thus find that if any one colour be taken away from white light, what

remains is another colour (called the *complementary* colour of that which is removed).

Two colours are called **complementary** when together they form white. Thus blue and yellow are complementary, red and green are complementary.

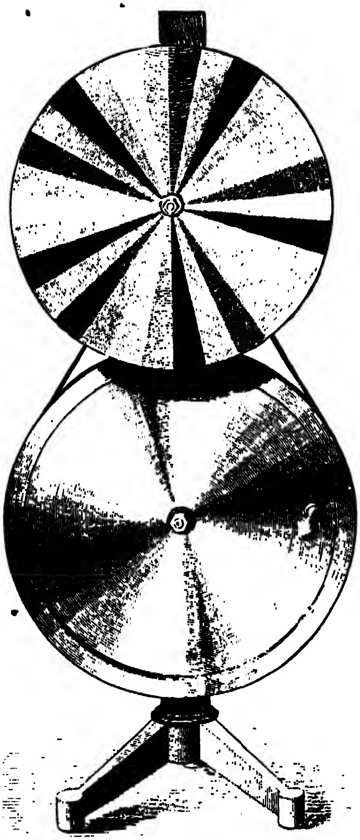


Fig. 120.—Newton's disc.

Mixture of Pigments not a Mixture of Colours.—Blue and yellow pigments when mixed together for painting make green. Blue and yellow lights, however, when mixed together form white. It must be remembered that a coloured object, not self-luminous, owes its colour to the fact that it absorbs some colours of the light which falls on it, reflecting and scattering the rest. Thus blue paint absorbs red and yellow, reflecting only green, blue, and violet. Yellow paint absorbs all but red, yellow, and green. Then when blue and yellow paints are mixed, the only colour which is not absorbed is green, which is reflected both by the blue and the yellow pigments.

Newton's Disc.—This is a disc mounted so as to be capable of being rotated rapidly by whirling apparatus and divided into radial compartments painted the colours of the rainbow as nearly as may be (Fig. 120). Any impression on the retina of the eye

lasts for an appreciable time. If the disc be rotated rapidly the impressions caused by the different colours overlap, and the disc appears a uniform gray. The stronger the light falling on the disc the more nearly does this gray approach to a white. It must be remembered that the disc is painted in seven colours, and that the white light obtained from their mixture cannot be expected to be more than that which would come from one-seventh of a white disc of the same size, therefore the rotating disc appears gray or dull white. If the colours be not very accurately painted, this gray will be tinged with the complement of the colour which is lacking. Very often the discs supplied by opticians are deficient in the blue part, and the resulting gray is yellowish in tinge.

Maxwell's Discs.—Clerk Maxwell invented an ingenious way of combining any two colours in any desired proportion. Different coloured discs of the same diameter have a hole at their centre so as to fit on to a whirling apparatus, and each has one radial slit cut in it. Two discs can be made to overlap each other by means of the slits, and so two colours can be combined in any desired proportion. The discs must be very rapidly rotated to combine the colours thoroughly. If the pace of rotation is too slow, flashes of colour will be seen instead of a uniform tinge.

Mixture of Complementary Colours.—Blue and yellow discs mixed in the right proportions give a good gray, and so do red and green.

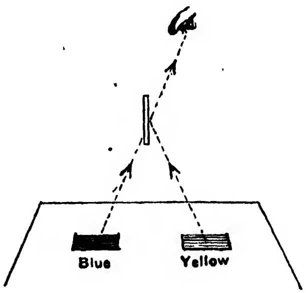


Fig. 121.—Complementary colours.

Make two paper squares of the same size, one yellow and the other blue, and lay them both on a black surface. Then hold a slip of plate-glass, as shown in Fig. 121, and one square can be seen by light transmitted through the glass and the other by light reflected. In this way the two squares may be made to coincide apparently, and by altering the position of the glass it can be arranged that the appearance is that of a single grayish-white square.

The eye is incapable of distinguishing between *pure colours* and mixed. It is believed that the retina is capable of transmitting to the optic nerve three primary colour sensations, viz. red, green, and purple. Red and green together produce the sensation of yellow, and the waves of sodium light apparently stimulate both the red and the green sensations. Red, green, and purple sensations combine into white. The three primary *pigments*, however, are yellow, pink, and blue, and these are employed in printing three-colour: a pink plate printed over a yellow plate receives finally an imprint in Prussian blue, the result showing all colours.

Duration of Impressions on the Retina—Complementary Colours.—When an object is gazed at steadily for some time, so that one portion of the retina receives the same impression all that time, the nerves of that portion become tired. If you gaze steadily at some red letters for a time and then look at the ceiling, you will see the same letters appear in pale green. The explanation of this fact is that one particular portion of the retina becomes tired of the sensation of red, and refuses to convey that sensation in full when white light is thrown on it, but conveys in full the rest of the white light, that is to say, the complementary colour, green; so that it receives the impression of faint green letters where the red has been.

Phosphorescence.—The light of phosphorus is due to chemical action, as in the light of a candle. But the name of phosphorescence is given to a class of phenomena in which no direct chemical action can be found. Certain sulphides have the property of shining in the dark, and 'luminous paint' is made from calcium sulphide. Its brightness disappears after it has been kept away from other light for some time, and it then needs to be exposed to light again to renew its luminosity. Light, falling on the surface of the paint, sets its particles in luminous vibration, and this vibration continues after the original source of the light is removed.

Fluorescence.—Herschel discovered that when the spectrum (p. 542) was allowed to fall on turmeric paper, the band of colour was lengthened at the blue end. It has been said that

there are radiations of lesser wave-length than the violet, which are invisible, but which have a powerful chemical action. It appears, then, that these radiations, after falling on turmeric paper and certain other substances, such as sulphate of quinine, are converted into visible rays. Professor Stokes has explained this class of phenomena as being of the same nature as phosphorescence. The particles of the turmeric paper are agitated by the ether vibrations, and in turn start new vibrations in the ether; but these new vibrations have always a greater wave length than those which were the original cause of disturbance. When these are removed the action ceases more quickly than in the case of phosphorescence, but the two phenomena are closely related. The Röntgen rays provide a notable example of fluorescence. These rays (which may differ from light as a sudden noise differs from a musical tone) cause fluorescence in various substances, in platinocyanide of barium among others. The Röntgen shadows thrown by bones, etc., on a fluorescent screen become visible as ordinary shadows.

Heating Effect of Light Rays.—When sunlight falls on matter which is not transparent, the vibrations of the ether are in some unknown way transferred to the matter, which becomes hotter. Light passes through a perfectly transparent substance without heating it. A burning glass made of ice can be used without the ice melting. But so soon as the radiations meet with an obstruction, they impart some of their energy to the obstructing matter. Some substances allow rays of some wave lengths to pass through, and not others. Thus rock-salt is *diathermanous*, that is, it allows the longer heat-waves to pass through it, and it is also *diaphanous* or transparent. Glass is transparent to light; but it stops the non-luminous heat-rays. The warmth of a greenhouse is due to the fact that the sun's rays of short wave length pass through the glass freely and warm the plants inside, while the longer waves radiated by the plants are stopped by the glass, in the same way that a glass fire screen stops the heat rays from a fire (see Radiation, HEAT, p. 397).

CHAPTER XIV

Double Refraction and Polarisation

Iceland Spar—Nicol's Prism—Polarised Light—Transverse Vibrations—Polariscope—Light Polarised by Reflection—Tourmaline—Nature of the Ether.

Double Refraction.—When a liquid of definite chemical composition becomes solid, *e.g.* when a mass of molten metal cools, or when a strong solution of a salt is allowed to stand, the particles usually arrange themselves in patterns, the nature of the pattern depending on the shape of the ultimate molecules of the substance. These patterns are called crystals, and have certain directions in them about which they are symmetrical. Thus rock-salt crystallises in cubes, and therefore has three directions or axes of symmetry at right angles to one another. The substance of which limestone is chiefly composed, calcium carbonate, crystallises in two distinct forms. One of these is called calcite, and is found in large quantities in Iceland, whence it gets its name of *Iceland spar.* It splits or *cleaves* very easily and perfectly in three directions, not at right angles, and so a *rhomb*, not a cube, of calcite can easily be obtained of a shape shown in Fig. 122. At two opposite corners of this rhomb, the three angles formed by the edges will be found to be all obtuse and equal, while at the other six corners two of the angles are acute and the other obtuse. Take one of the obtuse-angled corners and hold a pencil so that it makes equal angles with all three edges. The direction of the pencil is one of symmetry in the crystal, and, for a reason to be given, is called the optic axis of the crystal.

It should be noted particularly that the optic axis does not pass through any fixed point in the crystal, but is merely a

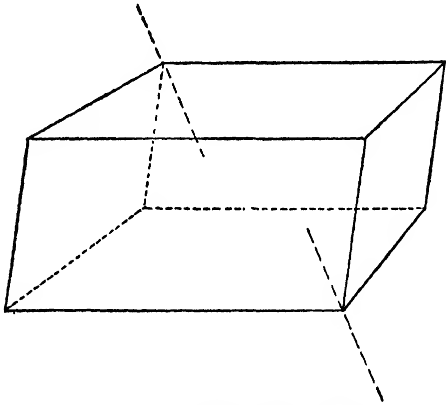


Fig. 122.—Rhomb of Iceland spar, showing direction of optic axis.

direction; we may in fact regard each point in the crystal as

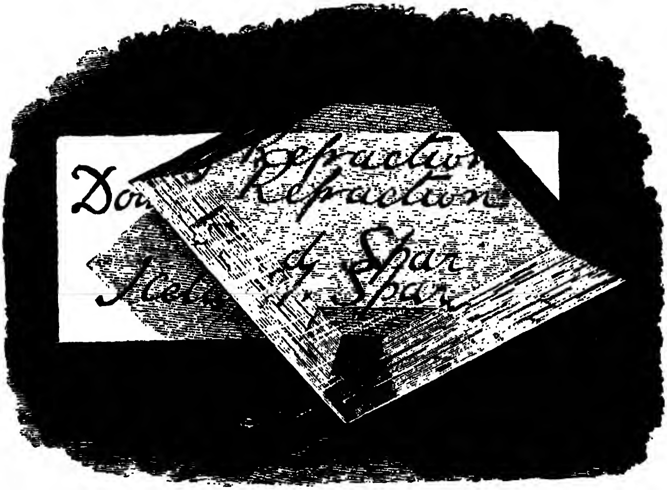


Fig. 123.—Double refraction.

having an optic axis of its own, all these optic axes being parallel to the one fixed direction in the crystal.

If a sheet of paper be seen through a rhomb of Iceland spar any writing on it will appear to be doubled, while if the spar be turned round, one of the images of the writing will turn round the other, which remains fixed (Fig. 123). This shows that a ray of light passing through this crystal takes two different paths. In one of these paths part of it follows the ordinary law of refraction, and is called the *ordinary ray*. The other part of it is called the *extraordinary ray*, this not only has a different index of refraction, but moves round when the crystal is turned round, so as always to keep in the same plane with the optic axis and the ordinary ray. In a plate of Iceland spar cut (not split) in a direction perpendicular to the optic axis, the double refraction is no longer apparent.

Nicol's Prism.—We now proceed to consider a plan of separating one of the rays (ordinary or extraordinary) from the other and examining it by itself. Nicol's prism consists of two wedges of Iceland spar cemented together with Canada balsam. The refractive index of Canada balsam is 1·55, lying between the two refractive indices, ordinary and extraordinary, of Iceland spar, which are respectively 1·66 and 1·49. Fig. 124 shows a ray of light falling obliquely at P on a Nicol's prism, and separated into the two rays PO and PE. The ordinary ray PO is incident on the dividing layer AB of Canada balsam at an angle greater than the critical angle (see p. 533), and so is totally reflected and does not get through at all. The extraordinary ray PE with a refractive index less than that of Canada balsam passes on and emerges at P′.

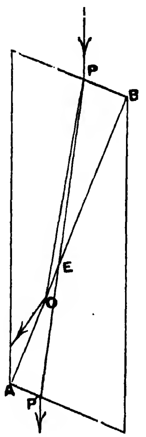


Fig. 124.
Course of rays through Nicol's prism.

Polarised Light.—If the light that has passed through a Nicol's prism be examined with a block of Iceland spar, it will be found to differ from ordinary light. Suppose that a small spot on a piece of white paper is being examined through a

Nicol's prism (called for short 'Nicol'). Only one spot is seen, because only the extraordinary ray comes through. Now hold a rhomb of Iceland spar above the Nicol and in general two spots are seen; these are of unequal intensity, and as the rhomb is turned round the intensity alters and at every quarter-turn one of the spots vanishes. Instead of the rhomb of spar use a second Nicol. When this is held similarly to the first Nicol, the spot is seen unaltered; but if the second Nicol be turned round, the light diminishes until a quarter-turn has been made, and then no light comes through at all, and these changes are repeated at every quarter-turn. If an arrangement be made by which only the ordinary ray is allowed to come through a block

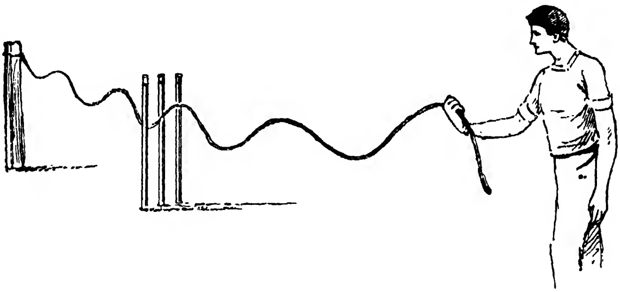


Fig. 125.—Plane polarised waves; vibrations permitted.

of Iceland spar, and this ray be examined by a second block of spar or a Nicol, the light is found to have the same properties as the extraordinary ray. Light that has passed through a Nicol's prism, or some such arrangement for separating the ordinary and extraordinary rays, is said to be *polarised.*

Transverse Vibrations—What is Polarisation?—Imagine a flat fish approaching a net, the meshes of which only run up and down, not across. The fish will be stopped by the net unless he turn himself on his side, when he will slip between the meshes without difficulty. This case bears some analogy to that of light polarised by one Nicol falling on a second Nicol. A better analogy may be found in the following experiment. Tie a rope to a post, pass it between upright posts or stumps as in

Fig. 125, then jerk the end of it. The waves that pass along the rope will not be stopped. If on the other hand the rope pass between horizontal railings the oscillations will be stopped, as in Fig. 126.

The only inference we can draw from the experiment of the crossed Nicols is that *the vibrations of light are transverse* to the direction of motion (see WAVE MOTION, p. 435). In ordinary light the 'ether particles' are not confined to any particular direction of vibration, but in a block of Iceland spar the vibrations are resolved into two at right angles to one another.

The optic axis of the crystal is a direction of symmetry, and the optical properties along the optic axis are different from those

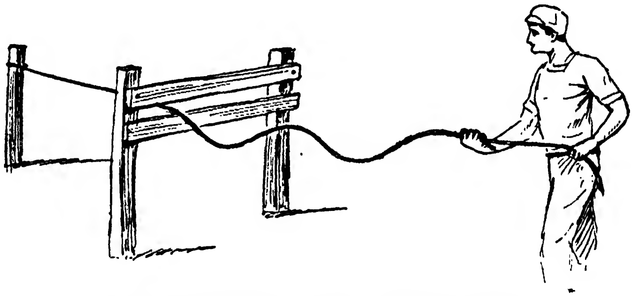


Fig. 126.—Plane polarised waves; vibrations stopped.

at right angles to it. A wave of light entering Iceland spar becomes two waves, in one of which the vibrations are perpendicular to the optic axis, and this wave will always travel through the crystal with the same speed in all directions. This is the ordinary ray. The vibrations of the other wave will be in the same plane as the optic axis. They may be at right angles to it, in which case the wave travels at the same pace as the ordinary wave. This is the case of light falling on a plate of Iceland spar *cut* perpendicular to the optic axis. Both waves vibrate perpendicular to the optic axis, and therefore travel at the same pace, so that no double refraction is seen. Now take a plate of Iceland spar *cut* parallel to the optic axis, whose direction is shown by the dotted line in Fig. 127. A wave of light

falling directly on this plate at the point A is resolved into two waves, one of which is caused by vibrations in the direction AO, along the optic axis, and the other by vibrations in the direction AP at right angles to AO. (Both AO and AP are at right angles to the direction of the light.) Now the elasticity of the vibrating medium, the ether, is supposed to be greater along the optic axis than at right angles to it. Consequently the first wave travels through the crystal more quickly than the second wave. Hence there are two refractive indices, the extraordinary being less than the ordinary.

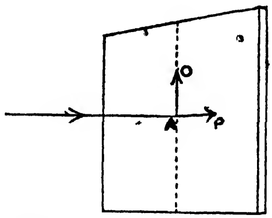


Fig. 127.—Plate of Iceland spar cut parallel to optic axis.

It seems then that the wave surface of light in Iceland spar (see Wave Motion, p. 440) is double, spherical for the ordinary ray and spheroidal for the extraordinary (Fig. 128). Along the optic axis, where the two velocities are the same, the two wave surfaces touch each other.

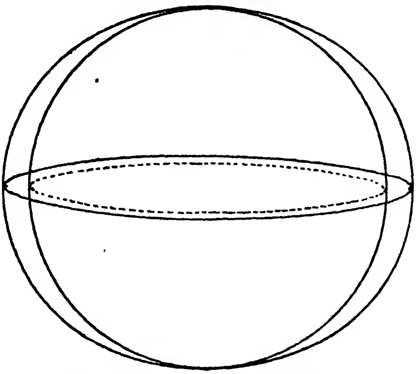


Fig. 128.—Wave surface in Iceland spar.

Polariscope—Interference of Polarised Light.—It has been stated that when light through one Nicol falls on another Nicol turned at right angles to the first, it is all cut off. But if a thin plate of crystal cut parallel to the optic axis be placed between the two Nicols, beautiful coloured rings appear. This is because the polarised light is resolved into two waves by the plate of crystal. These waves can partly get through the second Nicol, and having different velocities they are unequally retarded by the plate of crystal, and so by their interference give the coloured rings.

Thus in Fig. 129 a wave of light, caused to vibrate in the direction NS by the first Nicol, falls on the plate of crystal and becomes two waves, one vibrating in the direction AA′ and the other in the direction BB′. These waves falling on the second Nicol both become waves vibrating in the direction EW, and these waves interfere with one another, giving the beautiful coloured rings of the polariscope.

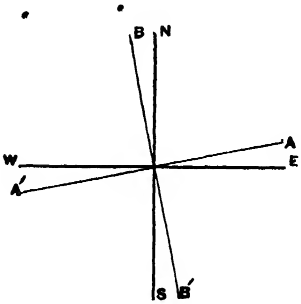


Fig. 129. Interference of polarised light.

Some crystals have three directions, in which their optical properties are different. This gives us three indices of refraction, and the wave surface becomes very complicated. In this complex wave surface there are two directions along which the light will give interference phenomena, and these are called the optic axes. Such a crystal is called biaxal, while crystals like Iceland spar and quartz are called uniaxal.

Light Polarised by Reflection.—Malus, a French savant, discovered, while examining the light reflected from the windows of the Luxembourg palace with a rhomb of Iceland spar, that one of the two images vanished when the spar was turned round to one particular position. This accident meant the discovery that light can be polarised by reflection. When light falls on a smooth surface of some transparent substance, the reflected ray is always more or less polarised, the amount of polarisation depending on the angle of incidence. Brewster found that polarisation was complete when the reflected

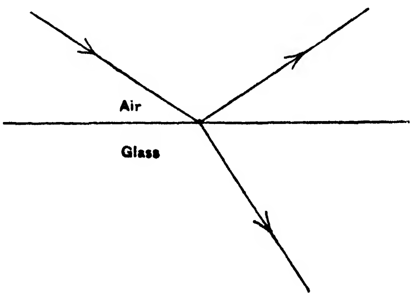


Fig. 130.—Light polarised by reflection.

ray was at right angles to the refracted ray (Fig 130). A glass reflector can thus be used in a polariscope instead of Nicol's prism.

Tourmaline.—The mineral tourmaline (which is a mixture of alumino-boro-silicates of various metals) is like Iceland spar in that it separates light into two rays, but to one of these rays it offers much more obstruction than to the other. In some varieties the ordinary ray is almost entirely stopped. Two plates of tourmaline can therefore be made into a simple form of polariscope called the tourmaline pincette (Fig. 131). The first plate acts as polariser and the second as analyser, the crystal to be examined being placed between the two tourmalines.

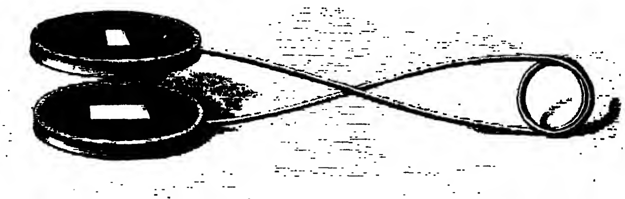


Fig. 131.—Tourmaline pincette.

Nature of the Ether.—To be capable of transmitting transverse vibrations, a substance must have a certain amount of elasticity of shape, that is, a tendency to return to its former shape after displacement. A liquid possesses this at its surface only. A gas does not possess it at all. A substance like blancmange possesses it, and all solids have it more or less. We might therefore suppose the ether to have some of the nature and properties of a solid, while it fills all space and is perfectly imperceptible to any of our senses. This "elastic solid" theory has served its purpose and is still useful; similarly the atomic theory is as useful as ever, though the word "atom" may be a misnomer. But no theory of the structure of ether and matter can be final. While with Newton and other giants the student of light gathers a few pebbles by the shore of the boundless ocean of knowledge, he may with advantage remember the instability of the castles that he builds in the sand.

MAGNETISM AND ELECTRICITY

BY

F. R. BARRELL, M.A., B.Sc.

PROFESSOR OF MATHEMATICS, UNIVERSITY COLLEGE, BRISTOL

FORMERLY INSTRUCTOR IN NATURAL SCIENCE IN H.M.S. *BRITANNIA*

PREFATORY NOTE

THE chapters on Magnetism have had the great advantage of attention from the late Lord Kelvin. He most kindly went through them carefully with Mr. J. E. P. Aldous during his voyage in the *Campania* in 1897 to attend a meeting of the British Association. He made a few alterations and suggestions, and he most encouragingly spoke of the chapters as being very satisfactory.

In deference to Lord Kelvin's strongly expressed opinion, the nomenclature 'red pole' and 'blue pole' has been followed to a great extent, certainly greater than the author had contemplated. These terms are of great value to seamen, as avoiding all possibility of confusion.

In the more theoretical part, the 'N. pole' and 'S. pole' notation is retained as consonant with modern practice.

The warm thanks of the author are tendered to his colleague, Professor A. P. Chattock, for his invaluable advice and criticism on several obscure points; and to Miss Alice Worsley, for the assistance given in reading proofs and in preparing photographs of apparatus.

The author has for technical information made free use of Messrs. Slingo and Brooker's *Electrical Engineering*, and Preece and Sivewright's *Telegraphy:* he feels also that he must be

indebted, perhaps unconsciously, to Professor Silvanus Thompson's *Electricity and Magnetism*, as it was from that book that his first non-mathematical ideas of the subject were derived.

By the kindness of the author, the editor has been allowed, in the editions of 1907 and after, to make many additions and changes in the matter dealing with Telegraphy, Telephony, Dynamos and Electric Motors on his own responsibility.

The British Westinghouse Electric and Manufacturing Company have kindly lent photographs of some of their standard design of modern electrical machinery, from which woodcuts have been produced.

MAGNETISM

CHAPTER I

MAGNETS

Lodestone — Artificial Magnets — Directive Couple — Magnetic Attraction and Repulsion — Magnetic Substances — Attraction through Bodies — Magnetic Induction—Soft and Hard Iron—Effect of Vibration—Time-lag — Effect of Temperature — Induced Polarity — Making a Magnet —Magnet Magnetised Throughout—Molecular Theories of Magnetism —Armatures.

1 **Lodestone.** — In several parts of the world an iron ore is found in the form of irregular stones which have the power of attracting to them and supporting small pieces of iron or steel. This ore was known to the early Greeks and called by them μάγνης (magnes), having been first found near Magnesia in Lydia. It is a compound of Iron and Oxygen (Fe_3O_4). These stones are lodestones or natural magnets; ordinary specimens are only capable of lifting a few grains, but some very powerful lodestones have been found. It is said that Sir Isaac Newton possessed one mounted in a ring, which weighed only 3 grains, but could lift more than 3 ounces; a magnificent specimen in the Edinburgh University supports 200 lbs.

The power of attracting in this manner is called Magnetism.

2 **Artificial Magnets** are pieces of hard steel which have been rubbed with a lodestone or with another artificial magnet, or magnetised electrically as described in § 23. They are usually

in the form of a horse-shoe, a bar, or a so-called 'needle' (Fig. 2).

3 If a magnet be dipped into iron filings (Fig. 1) the filings arrange themselves in thick clusters round the edges and ends of the magnet, leaving the middle portions quite free; this shows that the attracting force is greatest near the ends and prominent parts, and practically nothing near the middle. Hence the ends of a magnet are termed 'poles.' This falling off of the force near the middle is further illustrated by Fig. 7, in which the dotted curve shows the lengths of small soft iron rods that can be supported at various points along a bar magnet: four such rods are shown hanging from the magnet.

Fig. 1.—Lodestone with filings.

4 Now if any magnet be supported so that it can turn horizontally with ease, we find that it persistently sets itself so as to point with one end towards the North and the other end towards the South. Moreover, if we mark that end which points towards the North in one trial, we find that the same end points towards the North in any subsequent trial. Thus not only do the ends of a magnet differ from its middle but they differ from each other.

5 There are several different ways of showing that a free magnet points North and South.

1. *Magnetic Needle.*—This is a light flat piece of steel shaped as in Fig. 2. It should be fitted at the middle with a small cap having a centre of glass, agate, or some hard jewel, so that it can turn easily when placed on a hard upright sharp pivot. It is magnetised (*i.e.* made into a magnet) artificially, and when free to turn will set itself approximately North and South.

2. *Suspended Magnet.*—A lodestone, a bar-magnet, or a

magnetised knitting needle when suspended in a wire or paper stirrup by means of a thread, as in Fig. 3, will set themselves N. and S.; or—

3. *Floating Needle.*—Such magnets may be laid on a flat cork

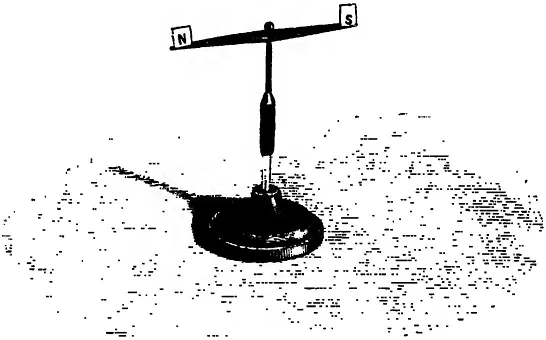


Fig. 2.—Magnetic needle.

and floated on water, they will then turn and set themselves North and South.

Common sewing needles will float if laid gently on water, being too light to break through the surface, and if previously magnetised they show this 'set of the needle' well.

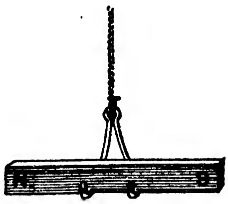


Fig. 3.—Bar magnet in stirrup.

6 The end which points towards the North is called the 'N. pole' of the magnet. It is often called the 'North-seeking Pole,' 'the Marked End' or the 'Red Pole,' since most magnets have the North-seeking pole indicated by a file mark or by being coloured red. The practice of colouring the N.-seeking pole red and the S.-seeking pole blue was introduced by the late Astronomer-Royal Sir G. Airy, and is approved by Lord Kelvin: Lord Kelvin has also called the N.-seeking pole a 'True South Pole,' for reasons which will be explained later (see § 37).

7 **Directive Couple.**—In the experiments with the floating

needles or magnets just described, it must be particularly noticed that there is *no tendency whatever* for a magnet to move bodily towards the North or in any other direction, hence there is no single resultant force acting on it. The magnet merely *tends to turn*, hence its red pole must be urged towards the North, and its blue pole towards the South with equal and opposite forces. These forces constitute a couple, which may be called the 'Earth's directive couple,' upon the needle; the directive couple is zero when the needle lies magnetic North and South, and is greatest when it lies magnetic East and West.

8 **Magnetic Attraction and Repulsion.**—We have seen that either pole of a bar magnet is able to pull or attract towards it any movable piece—say a small rod—of unmagnetised iron or steel. Now Newton's Third Law states that 'to every action there is an equal and opposite reaction'; hence when an iron or steel rod is brought near to either pole of a movable bar-magnet (suspended in a stirrup as in Fig. 3) we should expect that pole to be attracted by the rod; and since the rod is not magnetised, either end or even the middle of the rod should attract the magnet equally well. We find on experimenting that the conjecture is true, a magnetic needle can be made to spin rapidly by leading either pole with a piece of iron; and a magnet will cling to iron just as forcibly as iron will cling to a magnet.

9 If, however, instead of a piece of unmagnetised iron we present the red pole of a *magnet* to a magnetic needle, the blue pole of the needle is attracted and the red pole of the needle repelled.

And if we present the blue pole of the magnet to a magnetic needle the red pole of the needle is attracted and the blue pole repelled.

RULE—Like poles repel.
Unlike poles attract.

10 In the above experiments we cannot repel the red pole without at the same time causing the blue pole to approach; hence it is occasionally objected that there is no real repulsion of the red pole but merely an attraction of the blue pole.

The following experiment shows that there is a real repulsion.

A bar magnet is slung as in Fig. 4 by means of two V strings so that it cannot turn. A scale is fixed to a stand close behind the magnet. If now the red pole of another magnet be slowly brought near to the red pole, the suspended magnet can be repelled through two or three inches.

When the magnet is brought near to the suspended magnet, the magnetism of each is weakened—indeed the poles of one of them may be reversed if the approach be too close, we should then

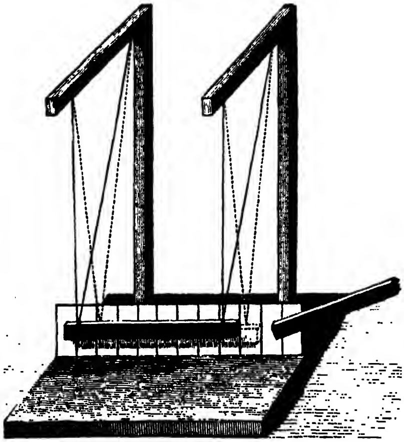


Fig. 4.—Magnetic repulsion.

get attraction instead of repulsion. Hence in this experiment we must take care to bring up our magnet to the suspended one very slowly. When the blue pole of one magnet is presented to the red pole of the other, the magnetism of each is increased, hence there is in this case no need of caution, and the suspended magnet can be attracted through a great distance.

11 **Magnetic Substances.**—Iron and steel are the only substances attracted by magnets with any considerable force. No other substances, except nickel and cobalt, are magnetic to any readily appreciable extent. An electromagnet which can lift 14 lbs. of

iron cannot lift one grain of copper, silver, gold, etc. Such substances can therefore be fairly called non-magnetic. Nickel and cobalt are attracted much less than iron, but still somewhat strongly. Faraday, who experimented with very powerful electromagnets, found that almost all substances are acted on to some extent by magnets. Some substances, which are feebly repelled, he called *Diamagnetic*, while those which are attracted he called *Paramagnetic*.

Paramagnetic.	Diamagnetic.
Iron	Bismuth
Nickel	Phosphorus
Cobalt	Antimony
Manganese, etc. etc.	Zinc, etc. etc.

12 **Attraction through Bodies.**—The attraction or repulsion of a magnet is not affected by any non-magnetic bodies placed between it and the iron or steel which it is attracting; thus, a board, a brick, or a pane of glass intervening will have no effect. Fig. 5 shows a magnet attracting an iron rod in a glass beaker; the attraction holds up both beaker and rod. A knowledge of this fact will show the absurdity of some advertisements of magnetic belts etc. which 'will send a current of magnetism through deal boards an inch thick'; for any scrap of magnetised steel inserted in the belt would act through such boards.

Fig. 5.—Magnetic attraction unaffected by glass.

13 In conducting experiments it is difficult to prevent unsuspected pieces of iron or steel from acting on instruments; keys and knives are easily detected, but wire in the brim of the hat and similar mysteries of clothing may be overlooked. Trouble may be caused in one room by a charwoman carrying iron buckets

in another room, or by bicycles in a neighbouring playground; the steamers on the Thames even affect the instruments in the laboratories of King's College.

14 **Magnetic Induction.**—A piece of iron or steel placed in contact with or even brought near to a magnet becomes itself a magnet. An ordinary piece of soft iron ceases to be a magnet immediately on removal, so indeed does hard iron or steel if its magnetisation has been very feeble; but hard iron and steel, after being at all strongly magnetised, retain their magnetism on removal.

15 **Soft Iron and Hard Iron.**—In the last paragraph we have pointed out a difference in the magnetic behaviour of soft iron and hard iron, but have not stated in what the softness or hardness consists. The distinction originally implied merely the mechanical quality that a soft iron can be easily filed, while a hard iron or steel can only be filed with difficulty; this mechanical softness is usually accompanied by the quality of becoming magnetised easily and of being demagnetised easily, and the mechanical hardness by difficulty of magnetisation and difficulty of demagnetisation.

It is well known that the mechanical qualities of iron and steel depend in a complex manner, not only on their chemical composition, that is on the percentage of carbon and other substances which they contain, but also upon the processes of hardening, tempering, and annealing, and also upon the strains which they have undergone. The magnetic qualities also depend in a complex manner on these conditions.

16 Until recently it has been supposed that soft iron acquires its magnetism immediately on the application of any magnetising force and loses it instantaneously on the removal of the force; however, the numerous experiments of Ewing, Hopkinson and Lord Rayleigh during the last few years have proved clearly that the magnetism of soft iron, especially of thick pieces, takes several minutes to rise to its full value, and further that when there is complete absence of vibration and when no demagnetising forces come into play, then soft iron retains a

high percentage of its magnetism, far more in fact than hard iron or steel. The following reasons account for this fact being so long overlooked. When a bar has been magnetised, its own poles, by their mutual attraction, set up a force tending to demagnetise the bar; obviously this tendency is greater when the poles are nearer together, hence in a bar which is short compared with its diameter the demagnetising force due to its own poles much diminishes the amount of its residual magnetism. In soft iron, which is demagnetised very readily, the influence of the ends is so great that in all bars of ordinary dimensions no trace of residual magnetism is found, and even when the length equals 50 diameters the residual magnetism is only one-tenth of that in a very long rod. The following results are selected from experiments quoted by Ewing.

	Magnetising Force.	Magnetic Induction.	Residual.	Per Cent.	Coercive Force.
Very soft annealed iron wire length = 400 diameters	17	13,500	11,000	82	1·9
Soft annealed rod length = 200 diameters	17	15,000	10,000	66	1·9
,, = 100 ,,	15	14,500	3,400	23	1·9
,, = 50 ,,	34	15,000	1,000	6·6	1·9
Soft annealed wire . .	42	15,400	11,400	74	1·9
Same wire hardened by stretching . . .	42	13,900	5,000	36	4·5
Pianoforte steel wire annealed	95	14,200	10,000	70	23
Same wire glass-hard . .	98	12,800	9,000	70	45
Soft gray cast-iron . .	200	10,000	4,000	40	7

17 All the numbers in this table refer to absolute C.G.S. measures, which are explained in Chap. III.

The first column gives a measure of the magnetising force [usually derived from a solenoid carrying an electric current, ELECTRICITY, p. 752]; the second column gives the magnetic induction produced by the force; the third column gives the magnetic induction which remains after the magnetising force has been removed; the fourth column gives the percentage of

induction which remains, and therefore indicates the 'retentivity' of the specimen experimented on; the fifth column gives the magnetising force which has to be applied in the reversed direction in order to destroy the residual magnetism; this force is usually called the 'Coercive Force' of the specimen, since it indicates the amount of coercion which has to be employed in order to make it give up the magnetism which it has acquired.

18 **Effect of Vibration.**—It is important to notice the remarkable modification which vibration produces in the foregoing results: thus in annealed soft iron the slightest tapping or vibration suffices to entirely destroy its residual magnetism, in fact its retentivity under vibration is zero instead of 70 or 80 per cent. On the other hand, when annealed soft iron is subjected to a magnetising force vibration increases the magnetisation, thus in one experiment a magnetising force of ·32 produced a magnetisation 20, which was, by tapping, sent up to 6600 at a bound. Similar results, though not so extreme, occur with hard iron and steel, thus with a hard unannealed piece of the wire last referred to, a residual magnetism 7000 fell to 2500 when the specimen was smartly tapped. When very powerful magnetising forces are employed tapping or vibration has only a slight effect.

19 **Time-lag.**—To illustrate the question of the time taken before the full magnetisation is produced we may notice that in experiments made by Lord Rayleigh on soft iron under weak magnetising forces, the magnetisation underwent during the first five seconds an increase of from 30 to 50 per cent on its instantaneous value, and a further increase of about 20 per cent in the first minute. In hard iron and steel time-lag is very rarely perceptible.

20 **Effect of Temperature.**—If the temperature of soft iron be raised while it is subjected to a weak magnetising force the first effect is to increase the magnetisation; after passing a temperature of about 700° C. (1200° F.) the increase is very rapid and may be ten or twentyfold, then on approaching a certain 'critical temperature,' which differs in different specimens and may be

from 770° to 800° C., the magnetism falls off very rapidly; and the whole of it is lost, while the temperature further rises 10° or 12°. Under moderate magnetising forces very little increase of magnetism is caused by a rise of temperature, and under powerful forces no increase occurs: but in all cases the magnetism entirely disappears at the 'critical temperature.'

The effects of temperature on hard iron and on steel, whether hard or mild, are of similar character; in general the harder the specimen is the lower is its critical temperature; under moderate forces a rise of 500° or 600° C. increases the magnetism, and under high forces it decreases it.

21 **Induced Polarity.**—When a piece of iron or steel is brought near to a magnet the end which is nearest to the red pole becomes a blue pole; and the end furthest from it becomes a red pole.

It is as though there were two kinds of magnetism which we may conveniently call red and blue magnetism, the blue magnetism being attracted and heaped up in the iron at the end nearer to a red pole, and the red magnetism repelled and heaped up at the further end of the iron. Since this magnetism appears to be 'induced' or 'led in' to the iron by the action of the magnet, the phenomenon is called 'Magnetic Induction.' The wire nail shown in Fig. 6 is attracted by the horse-shoe magnet and, being held down by a thread of cotton, remains suspended in mid-air like Mahomet's coffin. It is magnetised by Induction, and therefore can carry the cluster of filings near its point. The star-shaped piece of sheet-iron in Fig. 7 touches the bar magnet, and being magnetised by Induction is itself able to hold a square of iron hanging below it; then again the square being magnetised is able to carry the cluster of filings at its angles. So also the four small iron rods are magnetised, having S. poles, *s*, *s*, induced in their upper ends near to the N. pole of the bar magnet, and N. poles, *n*, *n*, at their lower ends.

22 We now see the reason for the formation of the clusters or bunches when a magnet is dipped into iron filings. Each individual filing near the N. pole of a magnet becomes itself

magnetised by induction. It has a N. pole and a S. pole. The

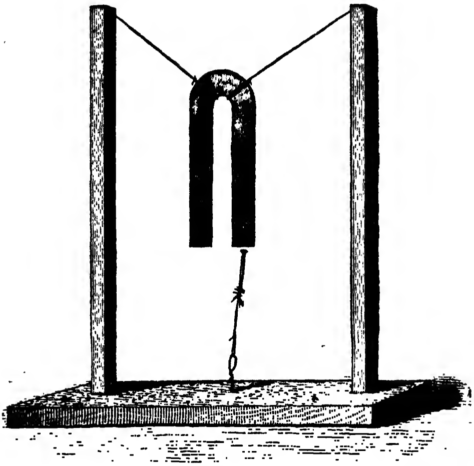


Fig. 6.—Wire nail magnetised by induction.

latter is attracted and the former repelled, so that the filing tends to set itself 'end on' to the magnet. The neighbouring particles, being also magnetised, are acted on by each other, and attach themselves together, N. pole to S. pole, forming thread-like chains of filings clustered together near the poles of the magnet.

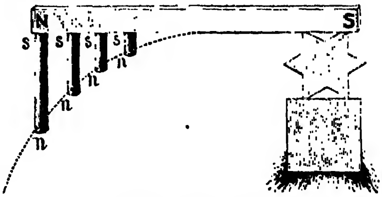


Fig. 7.—Iron star magnetised by induction.

23 **Making a Magnet**—Method of Rubbing.—In order to magnetise a steel bar, say a knitting needle or sewing needle, mark with a file or otherwise the end A which is to become the N. pole.

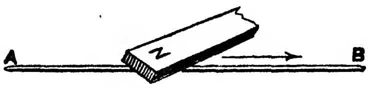


Fig. 8.—Magnetising a knitting needle.

Lay the needle on a table; take a bar (or horse-shoe) magnet;

place its N. pole on A, and pressing gently draw it several times from A to B, always in the same direction; then place the S. pole on B and draw it several times from B to A: the alternate rubbing with N. and S. pole may be repeated several times, but care must be taken with each pole to move in the proper direction for it, and also to move from extreme end to end of the needle at each stroke.

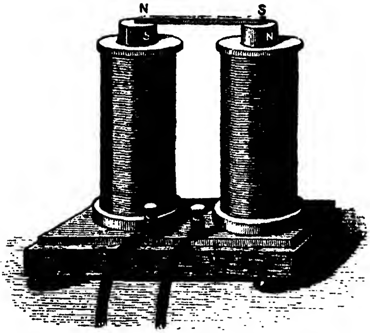


Fig. 9.—Magnetising by electromagnet.

24 Method by Hammering.—Lay the steel bar which is to be magnetised with one end on the N. pole of a magnet and the other end on the S. pole of another magnet, then strike the bar repeatedly with a mallet. Or better still, lay it across the poles of a powerful electromagnet (Fig. 9) and strike as before. In this case the bar must be just long enough to bridge the poles of the electromagnet.

25 **Magnet Magnetised Throughout.** If a magnetised knitting needle be broken at its middle point each half is found to be

Fig. 10.—Magnetised needle broken up.

a magnet. The ends which were N. and S. poles before breaking remain N. and S.; while the broken ends become N. and S. poles alternately, as in Fig. 10.

The half needles may be again broken into equal or unequal pieces, and these again and again broken, the fragments always

act as magnets, however small they may be. The poles of *very short* pieces of the needle appear weaker than the original poles: this is chiefly because the poles are so near together that the repulsion of one pole nearly equals the attraction of the other pole, and therefore nearly counteracts it.

26 Hence a magnet may be thought of as built up of an immense number of particles, each having a N. and a S. pole: in the body of the magnet the N. pole of one particle being in contact with the S. pole of the next particle neutralises it; but the unneutralised poles at the ends form the poles of the magnet. The diagram (Fig. 11) is intended to illustrate this internal structure.

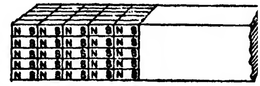


Fig. 11.—Structure of magnet.

27 **Molecular Theories of Magnetism.**—Weber suggested that in iron or steel the individual molecules are minute magnets each with a N. pole and a S. pole: if the iron be unmagnetised the molecules are arranged at random, so that, there being on the average equal numbers of molecules facing in all directions, the iron as a whole does not behave as a magnet. When the iron is subjected to a magnetising force the molecules are twisted round more or less, so that a large number face in the same or nearly the same direction, the iron then behaves as a magnet.

28 If this theory be correct it is clear that when all the particles are set exactly in the proper direction it is impossible to magnetise the iron more strongly, which had been discovered experimentally by Joule to be the case. When powerful electromagnets are employed to magnetise a body a limit to the magnetisation is soon reached; the body is then said to be 'saturated' with magnetism.

29 Ewing has modified Weber's theory so as to make it conform more closely with the facts. He supposes that, instead of the molecules being arranged quite at random, they are linked together in groups of two or more molecules, the molecules of each group being held together by the attraction and repulsion of their N. and S. poles. A possible stable arrangement of a square group of four molecules is represented in Fig. 12 by the

arrows in position I. The application of a moderate magnetising force from left to right, indicated by the two-barbed arrow, will deflect each molecule somewhat as in position II without breaking the tie which holds each pair of poles together; if after such a deflection the magnetising force be removed the molecules will fly back to position I. The application of a powerful magnetising force indicated by the treble-barbed arrow, will, however, break up the arrangement of the group and twist the molecules into a

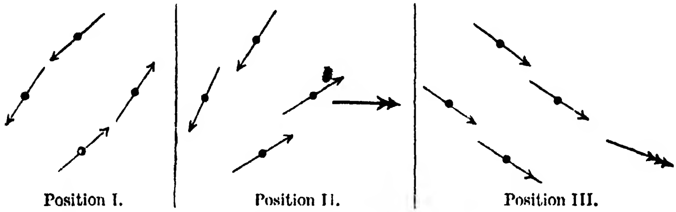


Fig. 12.—Imaginary grouping of molecules.

new position (III), in which new ties are formed between the poles; this position is a stable one, and will persist after the removal of the magnetising force.

30 We cannot enter into a complete explanation of the theory, but may point out that the broad distinction between soft iron and hard is probably due to the arrangement of the molecules in a group being such that the attractive bonds which hold the group together are weaker in soft iron than in hard iron; and that, when new groupings or arrangements of molecules are made by the specimen being magnetised, the new bonds formed are also weak in soft iron and stronger in hard iron. It is also easy to see that any vibration which causes the molecules to oscillate must assist the magnetising force to break up old groupings, and so to promote magnetisation; conversely, when the magnetising force is removed vibration must tend to break up the new groupings, and in soft iron, where the attractive bonds are weak, the slightest vibration suffices to break up all the groups.

31 **Armatures.**—'Permanent' magnets become gradually weaker

in course of time if left to themselves, owing to accidental jarrings and vibrations to which they must inevitably be subjected unless extreme precautions be taken to prevent it. This may be partially prevented in horse-shoe magnets by keeping a piece of soft iron, called an Armature, always across the poles, and in bar-magnets by keeping them in pairs with poles reversed and a soft iron armature across each pair of poles (Fig. 13). The armatures are magnetised by Induction, and the particles both in the bars and the armatures, having each a N. pole close to the S. pole of a neighbouring particle, form continuous chains tending to hold one another in position.

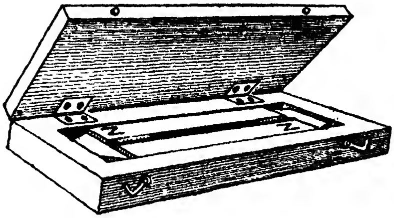


Fig. 13.—Pair of bar magnets with armatures.

CHAPTER II

TERRESTRIAL MAGNETISM

Magnetic Meridian — Variation — Inclination or Dip — Secular Changes — Other Changes—The Earth as a Magnet—Earth's Induction—Mariner's Compass—Deviation of the Compass—Thomson Standard Compass.

32 **Magnetic Meridian.**—Referring to § 4, we now remark that the direction in which a magnet points varies more or less from the true North and South in different parts of the world. The direction in which the red pole actually points (when undisturbed by magnets or iron near to it) is called *Magnetic North*, and the vertical plane passing through magnetic north is called the plane of the Magnetic Meridian, just as the vertical plane passing through the true North is called the plane of the True Meridian.

33 **Variation.**—The angle at any place between the true and the magnetic meridian is called the Magnetic *Declination* (in navigation and all nautical matters it is called the *Variation of the Compass*). The variation differs from place to place, and may be to the East or to the West; thus, in 1896, in London it was about 16°45′ W., at Plymouth about 18°30′ W., at New York 7° W., at Vancouver 20° E.

There is a line of No Variation passing over Hudson's Bay and to the East of S. America; one over Lapland, Persia, and Australia, and the 'Siberian Oval' Lat. 15° to 68° N.: Long. 108° to 158° E.

34 **Inclination or Dip.**—It was noticed by one of the early instrument makers, Norman, that though an ordinary compass

needle was perfectly balanced before being magnetised its red pole always showed a tendency to dip downwards after magnetisation. This is best shown by suspending a needle so that it can turn in the magnetic meridian about a horizontal axis. The needle must

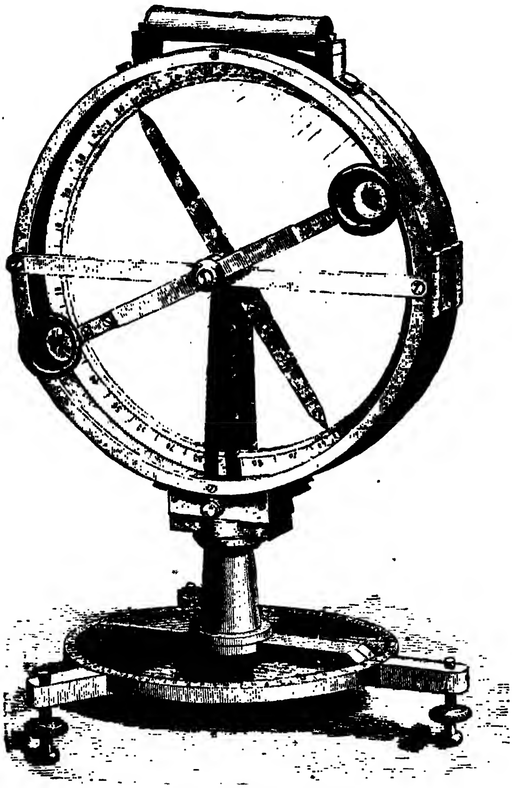


Fig. 14. –Dipping needle.

be very carefully balanced so that it will rest in equilibrium in all positions; it is then magnetised, and the red pole is found in England to dip downwards about 70°. As a rule, in the Northern Hemisphere the red pole dips downward, and in the Southern the blue pole dips. Near the equator there can be traced

round the earth a line, at all points of which there is no dip; it is called the *Magnetic Equator*. There is both at the north and south a Magnetic pole, where the magnetic needle stands vertical. The North Magnetic pole was reached by Sir James Ross (1830) in Lat. 70° N., Long. 96° 43′ W. The latest results, those of Roald Amundsen, are eagerly awaited. At the South Magnetic pole the needle has its blue pole downwards. This is stated to have been reached by Captain Scott's *Discovery* expedition in Lat. 72° 5′ S., Long. 156° 25′ E., and by the *Nimrod* expedition in Lat. 72° 25′ S., Long. 155° 16′ E. The angle through which the needle dips is called the Magnetic Inclination, or Dip of the Compass. The instrument for measuring it is the Inclination Compass, Dipping Needle, or Dip Circle. A simple form of it is shown in Fig. 14. both variation and dip. The following is a record of the variation and dip in London :—

Date.	Variation.	Inclination.	Date.	Variation.	Inclination.
1580	11°17′ E.	71°52′	1815	24°29′ Max.	
1634	4°6′ E.		1823	24°10′	69°3′
1660	0		1868	20°33′	68°2′
1705	10° W.		1880	18°40′	67°40′
1720	13° W.	74°42′ Max.	1900	16°29′	67°9′
1800	24°6′ W.	70°35′	1910	15°42′	66°52′

These changes are called 'secular' (*sæculum*, an age, century), because they take many years to run through any great range.

36 **Other Changes.**—There are very slight but regular daily changes in both variation and dip. The needle turns through about 10′, the movement of the red pole being towards the West from about 7 A.M. to 1 P.M., and thence back to the normal position at 10 P.M., which is maintained through the night.

Also a regular yearly movement is observed, which, like the former, is probably due to the influence of the sun and moon.

Further, there are occasional erratic movements of the needle, which, although very minute, are observed simultaneously

over wide areas. They are known as Magnetic Storms—a name which possibly suggests to the uninitiated the idea of a violent disturbance, though the effects are so mild as only to affect, by means of 'earth currents,' the delicate instruments used on long telegraph lines.

37 **The Earth as a Magnet.**—The behaviour of a magnet needle which has been described would be accounted for by considering the earth as a gigantic magnet, as was first pointed out by Gilbert, one of the physicians to Queen Elizabeth. Since unlike poles attract, there must be a blue pole deep seated below the North Magnetic pole of the earth, and a red pole below the South Magnetic pole.

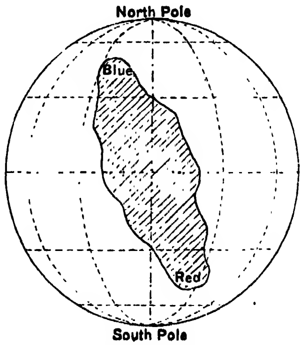


Fig. 15.—Imaginary magnet in earth.

It is this fact which has given rise to difficulty and some confusion in the names given to poles. If that end of the needle which points to the North be called a N. pole, we must call the North Magnetic pole of the earth a S. pole; if, on the other hand, we call that magnetic pole of the earth which is at the North a N. pole, then the North-seeking end of the needle must be called a S. pole. This confusion is referred to in § 6, and the advantage of the convention of 'blue' and 'red' poles can now be seen. The magnetic pole of the earth, which is at the North, is a 'blue' pole.

We may *picture* to ourselves an irregular iron core like a lodestone in the earth, as in Fig. 15. The picture is, of course, not correct, but is useful in helping the mind to connect together a number of independent facts. It is possible that the effects are in part produced by electric currents circulating within the earth.

38 **Earth's Induction.**—Since the earth behaves like an immense magnet, all bodies made of iron or steel, which are near to it, are magnetised by induction. As in previous instances, the

induction is greater, especially in the case of steel, if the bodies are subjected to hammering or violent treatment; it is greatest in the case of elongated bodies placed in the magnetic meridian and pointing downwards in the direction of the dip.

Thus, hammer heads and pokers are almost invariably found to be magnetised; they are not, as a rule, powerful enough to pick up filings, but their poles are very decided, and can easily be detected by their action on a common pocket compass.

Fig. 16.—Magnetised hammer.

Vertical columns and struts, steel masts, etc., will have (in the Northern Hemisphere) a red pole at their lower end and a blue pole at their upper end.

Horizontal beams and girders become magnetised with a red pole at their more northerly end. In a ship steaming north the propeller shaft will have a red pole forward and a blue pole aft.

39 **Mariner's Compass.**—This, in its simplest form, consists of a magnet needle fastened underneath a circular card; the top of

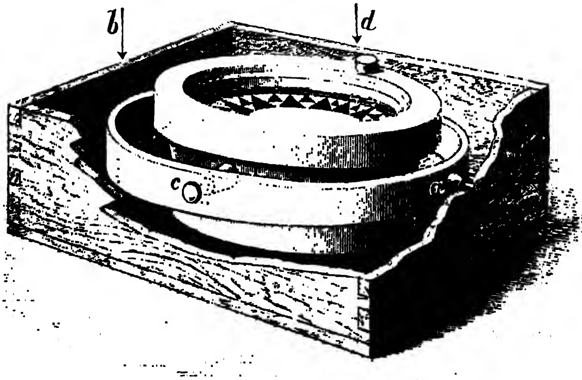


Fig. 17.—Mariner's compass.

the card is marked out by star-like radii into thirty-two divisions called the 'points of the compass'; one of these is marked N.,

and comes immediately over the north-seeking pole of the needle, it therefore indicates magnetic North. The circumference of the card is usually also marked out into degrees—90° easterly and westerly both from N. and from S.

The needle and card are supported by a central agate cap on a sharp pivot, which is fixed at the centre of the compass box. In order to keep the compass horizontal, in spite of the rolling and pitching of the ship, the box is supported on 'gimbals' (Fig. 17), that is, the box is pivoted to turn on one axis *ab* within a ring, while the ring itself can turn about an axis *cd* (perpendicular to *ab*) on a stand fixed to the ship. A mark—'the lubber's point'—indicates the direction of the ship's head. The stand on which the compass is fixed is called the 'binnacle.'

40 **Deviation of the Compass.**—In ships all masses of 'soft' iron, as we have seen, become magnetised by the earth's induction; but their magnetism is only 'temporary,' for although always present it *changes* when the ship changes her course, and heads in a new direction; this temporary magnetism also changes with changes of latitude.

41 All hard iron and steel parts of the structure, however, during building become more or less permanently magnetised by the vibrations due to riveting and general hammering; the nature of this magnetism depends on the position of the ship while building. The greater part of this gradually leaves the vessel after launching, but a part remains, usually called 'permanent magnetism.' There are also changes in the ship's magnetism which take place in the course of a few weeks or months when a ship cruises in a new district; the magnetism affected by these slow changes may be called 'subpermanent.' The ship's magnetism disturbs the compass, giving it a deflection, which in the Navy is called Deviation, but which Lord Kelvin calls the 'Error of the Compass.' The Deviation is made up of two parts, which are of quite different character: (1) The Quadrantal Error produced by temporary magnetism of horizontal soft iron structures; (2) The Semicircular Error produced by the permanent and subpermanent magnetism, and by vertical soft iron.

42 1. *Quadrantal Error.*—The combined effect of various horizontal masses of soft iron can be illustrated by the effect produced by a single large block. We will discuss the effect produced by

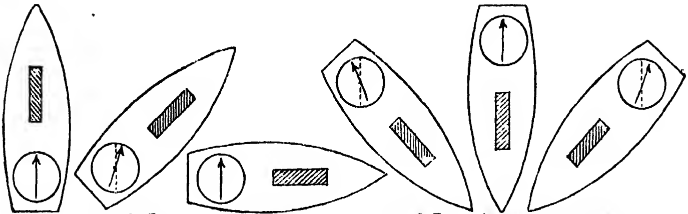


Fig. 18. Quadrantal error of compass.

a single large iron block lying fore and aft and placed amidships. In the diagrams the compass is shown further aft than this block.

When the ship heads due North the iron, being magnetised by the Earth's Induction, has a red pole 'forward' and a blue pole 'aft'; this blue pole is nearer to the compass and produces more effect on it than the 'forward red pole' does. It gives a direct pull on the N. pole of the needle, and therefore produces no deviation. But though in this position of the ship's head the mass of soft iron produces no deviation, it nevertheless has an important influence on the compass; for when the card is set swinging by any accidental disturbance the direct pull which the iron gives to the N. pole of the needle and the direct push which it gives to the S. pole of the needle form a 'directive couple,' which is added to that caused by the earth's magnetism, and therefore makes the needle oscillate more rapidly. When the ship heads East or West the iron is magnetised transversely, having a red pole to 'port' for an easterly course and to 'starboard' for a westerly course. It pulls each pole of the compass with equal force, and again produces no deviation. When the ship heads South the iron has a red pole 'aft' and a blue pole 'forward,' hence this 'aft red pole,' being nearer to the compass, gives a direct pull on the S. pole of the

compass, and there is also no deviation, but, as before, the iron adds to the earth's directive couple and causes the card to oscillate more quickly. Thus, on each of the cardinal points of the compass the error vanishes; in the intermediate quadrants it is alternately easterly and westerly, as shown in the diagram.

43 2. *Semicircular Error.*—The effect of the permanent and sub-permanent magnetism can be illustrated by considering the effect of a long horizontal magnetised bar lying 'fore and aft' with a red or N. pole towards the compass. When the ship heads North, there is no deviation, since the N. pole of the compass

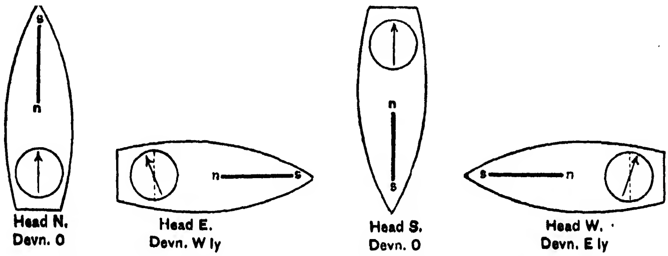


Fig. 19.—Semicircular error of compass.

needle is repelled directly towards the central pivot, but the directive couple due to the bar is opposed to that due to the earth, and may diminish it so much as to make the card swing very sluggishly. When the ship heads South, the S. pole of the compass needle is attracted directly, and there is no deviation, but the directive couple acting on the compass needle is increased.

When the ship heads East, the N. pole of compass is repelled and its S. pole attracted, from which there results westerly deviation; conversely, when the ship heads West, there is easterly deviation.

Thus the error vanishes when the ship heads North or South; it is easterly for one semicircle, westerly for the other.

44 Magnetised bars lying athwartships also produce semicircular error, but this error vanishes when the ship heads East or West.

The magnetism induced in vertical soft iron produces semi-

circular error, because its effect is similar to that of a magnetic pole, blue in the Northern hemisphere and red in the Southern hemisphere—placed at some point in the vessel, for example, at such a point as *n* in Fig. 19.

45 *Heeling Error.*—A further error appears when the ship heels over. This error is principally due to the vertical part of the subpermanent magnetism, and to induction in the soft iron lying athwartships or lying immediately below the compass: its effect is semicircular. If not corrected, the heeling error may be as much as two degrees for every degree of heel; in the case of a ship beating to windward, a distant object might on one tack bear twenty degrees differently from what it bore on the other.

46 **Thomson Standard Compass.**—The mariner's compass, adopted by the Admiralty and now almost universally employed, is that designed by Lord Kelvin—still best known by the name Sir William Thomson, under which most of his greatest inventions were patented. The chief improvements which he introduced in the compass are:—

47 1. A light paper rim instead of a heavy card, and several magnetised needles instead of one.

The card has a light aluminium ring AL, of say 10 inches

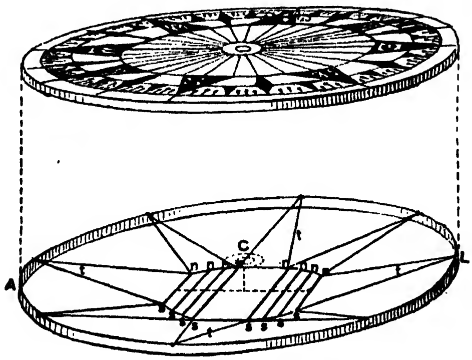


Fig. 20.—Thomson compass card.

diameter, connected by means of thirty-two silk threads to a central ring C, into which fits a jewelled cap (see the upper

part of Fig. 20); this rests on a brass pivot, with an iridium point. The 'points' and degrees of azimuth are marked on a paper disc, which is gummed to the ring AL; the central part of the disc is cut away for lightness.

Six or eight magnetised needles are arranged as at *n*, *s*, etc., in the lower part of Fig. 20, where the rim and needles are shown with the central ring and graduated disc removed. They are about as thick as No. 18 B.W.G. knitting-needles, and are attached to the ring AL by silk threads *t t* as shown.

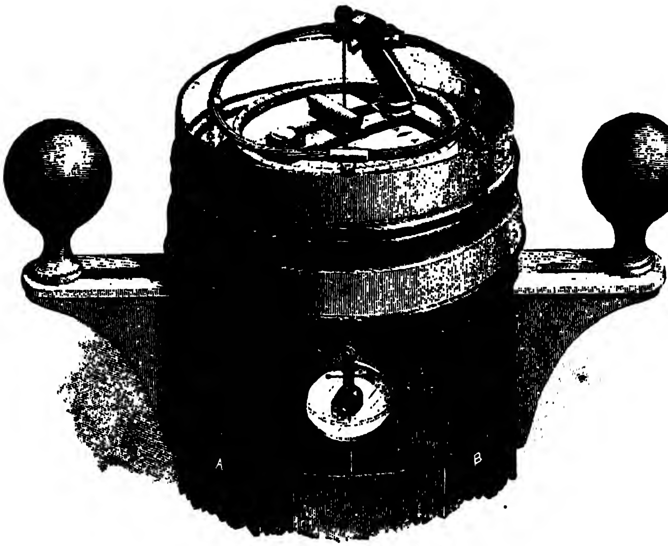


Fig. 21.—Thomson compass and binnacle.

The eight small magnetised needles have a greater magnetic moment for their weight than a single magnetised bar.

The card with needles complete weighs less than ½ oz., and as the weight lies chiefly in the rim it has the further advantage of swinging very slowly; the 'period' is from thirty to sixty seconds.

48 2. The compass card should be perfectly level. In the gimbals Sir Wm. Thomson introduced knife-edges instead of

one pair of cylindrical pivots. The ring of plaited wires in Fig. 21, which replaces the heavier ring *abcd* of Fig. 17, is supported on two knife-edges in a line with the spectator, the compass is slung from the plaited ring by chains instead of being supported by the other pair of pivots. To check the tendency to swing, the compass is placed in a hemispherical brass bowl with a lead weight soldered to its bottom. The bowl has a double bottom partially filled with castor-oil, which has a great effect in checking vibration. The whole weight of bowl and oil is about 17 lbs.

The other improvements consist in correcting the errors of the compass by means of bar magnets and iron balls attached to the binnacle.

49 3. Two large soft iron balls are bolted firmly to the binnacle on a level with the compass-card, and counteract the quadrantal error due to magnetism induced in the soft iron of the ship by themselves producing an opposite quadrantal error, which vanishes when the ship heads N., E., S., or W., and which is westerly for N.E. and S.W. courses, and easterly for S.E. and N.W. courses. Their size and distance from the compass must of course be adjusted to suit the magnetic conditions of the ship.

50 4. Bar magnets to correct the 'semicircular error' are placed in long horizontal holes in the binnacle. There are two vertical rows of horizontal fore and aft holes inside doors at A and B, about 5 inches from the central line of the binnacle; magnets placed in these correct the error produced by permanent and sub-permanent magnetism in fore and aft portions of the ship's iron; their effect can be increased by placing them in the higher holes, or decreased by placing them lower. Similarly inside the door at B there is a row of holes running athwartship for the insertion of magnets to correct the semicircular error arising from transverse beams and other thwartship iron.

51 5. 'Heeling error' is corrected by a vertical magnet or group of vertical magnets suspended vertically under the compass card; this can be raised or lowered by a chain fastened to pegs inside the door A.

52 6. The Flinders bar is a round bar of soft iron about 3 inches in diameter, and of a length (from 6 to 24 inches) suitable to the particular ship. It is placed vertically outside the binnacle, usually on the fore side, and so cannot be seen in Fig. 21. This bar counteracts the magnetism which is induced in vertical soft iron by the *vertical* component of the earth's magnetic force. The Flinders bar becomes temporarily a magnet with its red pole down or up, according as it is North or South of the magnetic equator.

53 7. The Deflector is an instrument, used with Thomson's compass, for adjusting it to magnetic North, when no sight of sun or stars or landmarks are available.

CHAPTER III

Magnetic Measurement

Measurement of Magnetic Strength—Magnetic Field—Intensity of Field—Number of Lines of Force—Measure of Magnetic Induction.

54 **Measurement of Magnetic Strength.**—One magnet may be much more intensely magnetised than another, and consequently its poles more powerful. This renders it necessary to have some method of measuring the *strength* of the pole, the first step towards which is the selection of a unit or standard magnetic pole. The following standard has been chosen:—

Unit pole—A unit pole (whether N. or S.) is one such that when placed at a distance 1 centimetre from another unit pole it exerts on it a force of 1 dyne.

A pole which exerts a force of m dynes on a unit pole placed at a distance 1 centimetre is said to have a strength m. Coulomb, by experiments with his torsion balance, proved that the force exerted by one pole on another is inversely proportional to the square of the distance between them; he further proved that the force is directly proportional to the product of the strengths of the two poles.

Hence a pole of strength m placed r centimetres away from a pole of strength m' exerts on it a force $\frac{mm'}{r^2}$ dynes.

55 **Magnetic Field.**—The space which surrounds any magnet clearly differs from a space which is not near to a magnet, for in the one a force acts on any small magnet or piece of iron which may happen to be present, and in the other no force acts. For

this reason we call the space surrounding a magnet the *field* of the magnet, or simply a 'magnetic field.'

Anywhere near the Earth there exists a magnetic field due to the Earth's magnetism, but it is very weak compared with the field of a common steel magnet.

56 The character of a magnetic field may be very readily examined as follows:—Lay a sheet of smooth paper over a magnet, and then sift some fine iron filings through a piece of gauze so that they are sprinkled evenly over the paper, tap the paper gently, and you will find that the filings arrange themselves in a set of curved lines from pole to pole, and the space above the magnet itself is left almost free from filings.

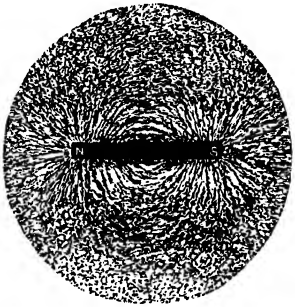


Fig. 22.- Lines of force.

57 If, now, a small needle, well magnetised, and having N. pole downward, be lowered by a longish thread over any point of the paper, the needle will be

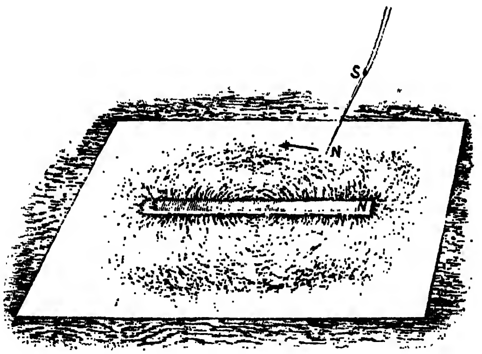


Fig. 23.—Needle following lines of force.

driven so that its point traces out one of lines marked by the filings (Fig. 23), and it will travel towards the S. pole of the magnet. Or if a short piece of magnetised needle be suspended

by a thread at its middle point it sets itself tangentially to the lines of force when lowered near to the paper.

58 These lines, along which there is a tendency to drive a north magnetic pole, are called 'lines of force'; a study of the lines of force belonging to any magnetic field gives very useful information concerning the field.

Fig. 24 shows the field due to two magnets with opposite poles towards each other.

Fig. 25 shows the field when similar poles are towards each other.

A steel bar which is irregularly magnetised has, in addition

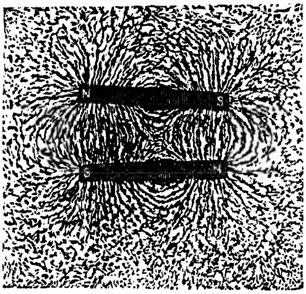


Fig. 24.—Lines of force.

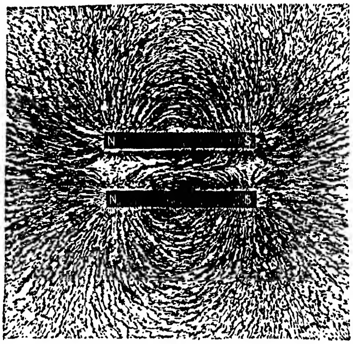


Fig. 25.—Lines of force.

to the poles at each end, irregular poles, which are called consequent poles.

59 **Intensity of Field.**—The intensity of the magnetic field at any point is measured by the force which would act on a unit pole if placed at that point.

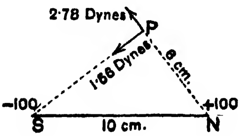


Fig. 26.—Diagram of magnetic forces.

As a rule, the intensity of the magnetic field changes as we pass from one point to another; for example, consider the field due to a magnetised wire 10 cm. long, the strength of each pole being 100.

At a point in S N produced distant 1 cm. from N ($\therefore$ 11 cm. from S) the intensity of the field $=\frac{100}{1}-\frac{100}{11^2}=99$ (approx.)

at 2 cm. from N " " $=\frac{100}{2^2}-\frac{100}{12^2}=24$ "

at 5 cm. from N " " $=\frac{100}{5^2}-\frac{100}{15^2}=3{\cdot}5$ "

at 10 cm. from N " " $=\frac{100}{10^2}-\frac{100}{20^2}={\cdot}75$ "

At the point P, which is 8 cm. from S and 6 cm. from N, the force on a unit N. pole is $\frac{100}{8^2}=\frac{25}{16}$ along PS, and $\frac{100}{6^2}=\frac{25}{9}$ along NP, and since these are at right angles; the intensity of field

$$=25\sqrt{\frac{1}{16^2}+\frac{1}{9^2}}$$

$$=\frac{25\sqrt{81+256}}{16\times 9}=3{\cdot}2 \text{ approx.}$$

The field of the Earth's magnetism is practically uniform over moderate distances, but, like gravity, it changes appreciably in distances of say 50 miles or more. At London the intensity of the earth's field was ·466 in 1890, its horizontal component being ·182.

60 **Number of Lines of Force.**—At any point near to a magnet there is a magnetic force acting in some direction or other, hence through every point in space a line of force can be drawn, and the whole space surrounding a magnet is densely packed with an infinite number of lines of force; it is a few of these that are indicated by the filings in the above manner. Now if we start from any two or three points near together and follow the lines of force from them, we find that these lines sometimes open out wider from each other, and sometimes close in towards each other; hence, although the number of lines of force be infinitely great, we may speak of them as being more densely packed together in some places and less densely in others. Wherever the lines are crowded together, as for example near to the poles of a magnet, the magnetic force is great, and wherever the lines are sparse the force is slight. There is a convention as to lines of force in diagrams and in calculations,

it is usual to represent the compactness or sparseness of the lines by actually drawing or counting only a finite number of them in proportion to the intensity of the field: thus if the intensity of the field be 10, we draw ten lines passing through each square centimetre taken perpendicular to the lines; whereas if the intensity of the field be $\frac{1}{7}$ we draw but a single line for every seven square centimetres taken perpendicular to the lines.

61 **Measure of Magnetic Induction.**—It is clear that in one sense, there can be no lines of force within the material of a magnet or of magnetised iron, for a solid thing such as the pole of another magnet cannot move within the material of the magnet, and we have so far considered a line of force simply as a line along which such a pole would be driven. Yet if we imagine a small cavity hollowed out within a magnet, the pole of another magnet would be free to move within this cavity; and there would be a strong force tending to make it move, for the magnet is magnetised throughout, and the walls of the cavity would therefore become 'poles.' The force within the cavity depends upon its shape, and is greatest for a narrow flat slit or 'crevasse' cut perpendicular to the direction of magnetisation, one wall of such a crevasse would be a broad flat 'red' pole, the other wall a broad flat 'blue' pole; the field of force between these flat poles is usually very intense, being measured, as all other fields of force are, by the force which would be exerted on a unit pole placed in the crevasse: the measure of the intensity of this field is called **the Magnetic Induction** within the metal; it may be indicated by the number of lines of force (here called lines of Induction) drawn per square centimetre.

ELECTRICITY

FRICTIONAL ELECTRICITY

CHAPTER I

Electrification

Fundamental Experiments—Deductions from Experiments—Vitreous or Positive—Resinous or Negative—Conductors and Non-Conductors—Insulators—Both Electricities Equally Produced—Proof Plane—Electric Induction—Two Electricities or One—Gold-Leaf Electroscope—Use of Electroscope—All Bodies can be Electrified—Electrical Series.

Fundamental Experiments.—In quite early days it was known that amber when rubbed could attract straw, dry leaves, and other light bodies. The fact is said to be mentioned by Thales of Miletus (B.C. 600), and certainly was by Theophrastus (B.C. 321), and Pliny (70 A.D.) From the Greek word ἤλεκτρον (electron), meaning amber, is derived the name of the modern science 'electricity.'

No further experiments in electricity are recorded until late in the sixteenth century, when the celebrated Dr. Gilbert of Colchester, referred to above, found that almost all bodies when rubbed behave in a similar manner.

The simple facts of electricity are best shown by a glass rod rubbed with silk, or a rod of sealing-wax rubbed with flannel or catskin. To obtain good results in friction experiments, all articles used should previously be thoroughly well dried by warming them for some time before a fire.

Experiment I.—Take either the glass rod or the sealing-wax

rod, and after well rubbing with the silk or the catskin, hold it two or three inches above a little heap of pounded glass, snips of paper, bran or any light pieces: the pieces are attracted vigorously to the rod, but immediately on touching it they are as vigorously repelled, so that the heap is scattered in all directions. One or

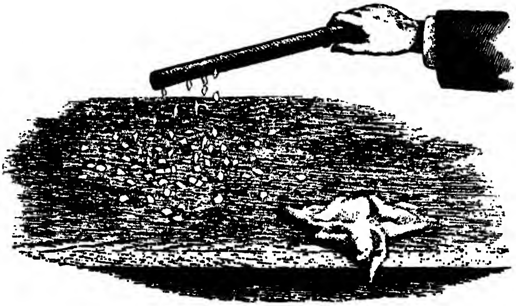


FIG. 1.—Electrified rod.

two stray pieces of paper may get flat on to the rod and cling to it for a minute or two before being repelled. Small pieces of gold-leaf may be lifted five or six inches, and will dance up and down between the rod and the table.

Experiment II.—Balance a common lath or a straw at the

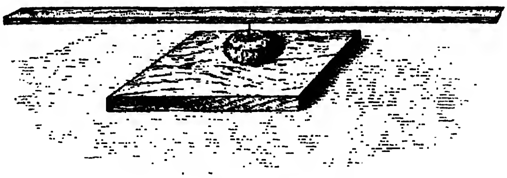


Fig. 2.—Lath balanced on point.

middle on a point; or hang up by a thread a wire with a cork at each end. The glass rod after rubbing with silk or the sealing-wax after rubbing with catskin will attract either end of the lath, etc., and by keeping the rod just in front of an end of the lath it can be made to spin rapidly.

Experiment III.—Suspend a pith ball—any light body, such

as the slip of cork shown in Figs. 4 and 5, a feather, a child's toy bladder will serve as well—at the end of a cotton thread: either rod, after rubbing, will attract the ball. The attraction is not affected when the body is allowed to touch either rod.

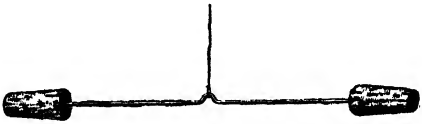


Fig. 3.—Suspended wire and corks.

Experiment IV.—Suspend the ball at end of a dry silk thread, or of a thread freshly drawn out from glass or shellac. At first either the glass or the sealing-wax rod will attract the ball, but if the ball be allowed to touch the glass rod, it will

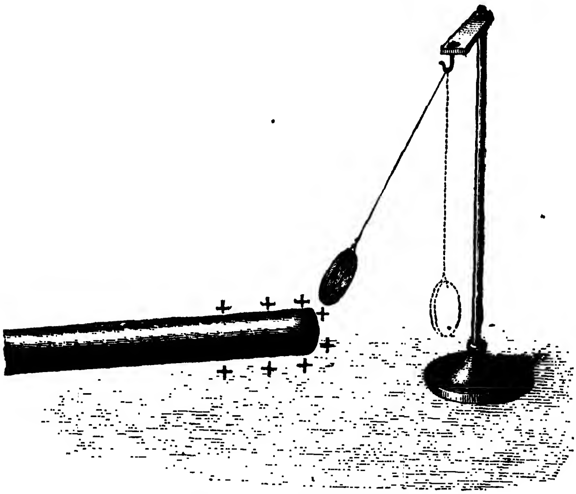


Fig. 4.—Slip of cork attracted.

afterwards be repelled by the glass rod and attracted by the sealing-wax. If, on the other hand, it touch the sealing-wax, it is afterwards repelled by the sealing-wax and attracted by the glass.

Experiment V.—The ball suspended as in Exp. IV. will, after touching either rod, attract another suspended ball.

Experiment VI.—Take two silk-suspended balls. Let both touch the glass or both touch the sealing-wax, they will repel one another. Let one touch the glass and the other touch the sealing-wax, they will attract one another.

Deductions from Experiments.—Bodies which after rubbing attract as in the above experiments are said to be *electrified.* Exp. V. shows that by touching another body they can pass on to it their power of attracting, *i.e.* they electrify it. The 'something' which causes the attraction is called *Electricity;* and an electrified body is said to be 'charged' with electricity. We may say that electricity is *produced* by friction, but we must be careful only to give to the word 'produce' its literal meaning, 'to lead forward,' and not think of electricity as being 'created' by friction.

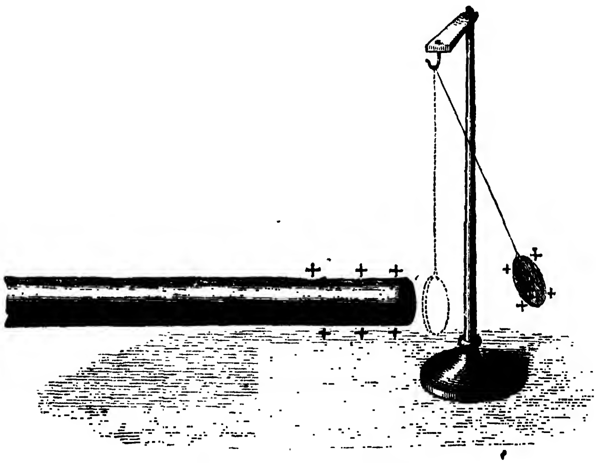


Fig. 5.—Slip of cork repelled.

Exp. IV. shows that the electrified glass acts differently to the electrified sealing-wax; hence there are two kinds of electrification, or we may say there are two kinds of electricity. The *Glass* Electricity is called **Vitreous** or **Positive**; the *Sealing-wax*

Electricity is called **Resinous** or **Negative.** It was customary until some twenty years back to speak of electricity as a fluid, and in the florid descriptions of newspaper reports we still read of the electric fluid. The objection to the word fluid is that electricity (although it will pass or flow from one body to another) is, in all probability, not a substance; there is no 'stuff' in it as there is in water or in air; similarly, heat will flow from a hot body to a cold one, yet heat is not a fluid.

Exp. VI. shows that bodies electrified in the same way repel one another; bodies electrified in the opposite way attract one another. This fact may be expressed in the law—

"LIKE *electricities cause* REPULSION;
UNLIKE *electricities cause* ATTRACTION."

Hence Exp. IV. shows that when a body touches an electrified rod it obtains from it electricity of the same kind as that of the rod, for it is afterwards repelled by it.

Conductors and Non-Conductors.—If the silk-suspended ball of Exps. IV. and VI., after being charged by one of the rods, be touched by the hand or by a piece of metal, coal, linen, cotton, or any damp body held in the hand, it immediately loses its power of attracting and repelling. It is no longer charged; it has lost its electricity, and it is natural to say that the electricity has escaped through the body which has touched the ball.

If, however, the ball be touched by dry ebonite, glass, shellac, wax, or silk, it does not lose its electricity. Bodies which allow electricity to pass along them are called **Conductors.** Bodies which do not are called **Non-Conductors** or **Insulators** (from *Insula*, an island, since bodies supported by non-conductors are converted into little islands, so far as electricity is concerned). We now see why the cotton-suspended ball of Exp. III. was not affected when allowed to touch the rod, for so soon as electricity passed to the ball from the rod, it was conducted away through the thread.

Whenever we wish to electrify bodies and make them keep their charge during an experiment, we must insulate them by

fixing them to glass or ebonite supports, or suspend them by silk threads.

The electrified bodies which we have described so far have all been surrounded by, and in contact with, air; hence we see that ordinary air is a good insulator, otherwise the glass rods, pith ball, etc., would very soon have lost all their electricity by leakage through the air. It is found that all dry gases at the ordinary pressure are good insulators.

Both Electricities Equally Produced.—A small cap of flannel is made to fit over the end of a sealing-wax rod, and a dry silk thread fastened to the cap so that it can be lifted from the rod without being handled. If now the cap be twisted briskly on the end of the rod, we find that although the rod with cap on, when presented to an electroscope (see p. 666), produces no effect, yet the cap when lifted off by the silk thread is charged positively, and the rod is charged negatively. This proves that both electricities are simultaneously produced, and that the amounts produced are equal; for, when presented together to the electroscope, the effect of each is neutralised by that of the other.

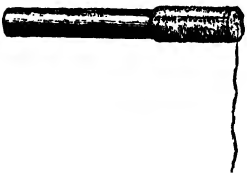


Fig. 6.
Sealing-wax and flannel cap.

Proof Plane.—This is a small flat piece of tinfoil (any metal will do as well), fastened at the end of a glass or ebonite handle; it is used to test the electrical condition of a body. If any part of an electrified body be touched by the proof plane the latter will, as seen in Exp. IV., take from the body a specimen of the electricity at that point. If the plane be then presented to a silk-suspended ball charged with positive electricity, the latter will be repelled or attracted according as the plane is positively or negatively charged.

Fig. 7.—Proof plane.

The gold-leaf electroscope gives a more delicate test.

Electric Induction.—If an electrified (say +) rod be brought near to an uncharged insulated metallic body A, we find by

means of the proof plane that the end of the body nearest to the rod becomes charged with negative, and the more remote end with + electricity, the middle parts being neutral. When the rod is removed A shows no signs of electrification. Those charges of electricity are said, as in Magnetism, to be induced, and the phenomenon is called Induction. Usually for such experiments we use hollow brass bodies, or blocks of wood coated with tinfoil of shapes shown in the figure and insulated on glass rods; they are often called 'conductors,' though strictly the word should be kept for all bodies which conduct. Induction may also be shown thus: two uncharged insulated conductors A, B are placed in contact, and a charged rod brought near to A. This induces a negative charge on A and

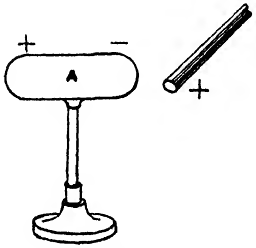


Fig. 8.—Induction.

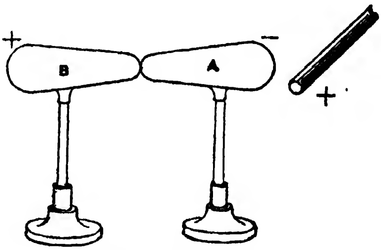


Fig. 9.—Induction.

a positive charge on B. If now A and B be separated and the rod subsequently removed, each conductor retains its charge, and can be tested directly with gold-leaf electroscope or suspended ball without the help of the proof plane.

After testing, A and B may be discharged (*i.e.* made to give up their electricity) by touching them with the hand or a wire, etc.; if they be again placed in contact and the rod again brought near A, they may be electrified as before, and the process repeated any number of times. If the rod be very strongly electrified and brought very close to A, the charges thus obtained will also be strong.

The above experiment succeeds equally well if a plate of glass, vulcanite, ebonite, or any other insulator be interposed

between the electrified rod and A. This proves that although electricity CANNOT PASS through non-conductors, yet it *can* ACT through them.

Hence it appears that by the help of induction we can obtain from two conductors a practically unlimited supply of electricity. The question naturally occurs to us, 'Where does the electricity come from?' One simple answer is as follows—All unelectrified bodies may be thought of as containing a practically unlimited supply of + electricity (whatever it may be); and an equal unlimited supply of – electricity (whatever it may be); the attractions and repulsions of these neutralise one another; a body which has an excess of + electricity or a deficiency of – electricity is positively electrified and *vice versâ*. Now if we extend the law given on p. 661, and say not only that like electricities *cause* repulsion and *vice versâ*, but that '*like electricities* REPEL ONE ANOTHER,' and '*unlike electricities* ATTRACT ONE ANOTHER,' we have accounted for all the facts described so far.

Two Electricities or One?—The mind may be inclined to rebel when called on to imagine all bodies as possessing these supplies of TWO electricities. A simplification can be made by accepting Franklin's suggestion that there is but ONE kind of electricity; that all unelectrified bodies contain a certain normal (*i.e.* usual, regular, or natural) amount of this electricity; that positively charged bodies are those with more than the normal amount, and negatively charged bodies those with less than the normal amount. This still leaves the difficulty that the normal amount of electricity in a body must be practically unlimited, for to produce a very intense negative charge a very great amount of electricity would have to be withdrawn from it. Further, it gives no help towards understanding the real nature of electricity. We will for the present accept the 'Positive Electricity and Negative Electricity' view of the question, for it gives a convenient language in which to describe and discuss our experiments.

It must be carefully noticed that an unelectrified body with its equal amounts of + and – electricity may be charged

positively (*i.e.* caused to have an excess of + electricity) in three ways:—

(1) by giving it more + electricity;
(2) by taking away − electricity;
(3) by both giving + and taking away − simultaneously.

So a positively electrified body may have its charge weakened in three ways:—

(1) by taking away + electricity;
(2) by giving it − electricity;
(3) by (1) and (2) simultaneously;

and any one of these ways, if pursued far enough, will soon equalise the amounts of + and − electricity in the body (*i.e.* discharge it), and then give it an excess of − electricity (*i.e.* charge it negatively).

Gold-Leaf Electroscope.—In order to detect the existence of feeble charges of electricity, we require a more delicate instrument than the silk-suspended ball; the gold-leaf electroscope is extremely sensitive. A convenient form is shown in Fig. 10. It consists of a rectangular metal frame closed in with plate glass at front and back: through the top of the frame passes a stout ebonite rod, and through the ebonite is fitted a brass wire, which is thus well insulated from the frame by means of the ebonite: at the upper end of the brass wire is a small brass plate or knob, at the lower end are two strips of gold-leaf about 5 centimetres (2 inches) long hanging flat against each other. If we bring a positively electrified rod near to the upper plate, − electricity is attracted into the plate, and + electricity is repelled through the wire into the gold leaves. The leaves being similarly electrified repel one another and open out as in Fig. 10. Now touch the plate: the + electricity endeavouring to get as far as possible from the electrified rod will escape through the body to the earth: the leaves will no longer be electrified, and will therefore close together again (Fig. 11). Remove the finger from the plate: the − electricity on it is unaffected, being still attracted by the electrified rod. Now remove the rod, the − electricity, being

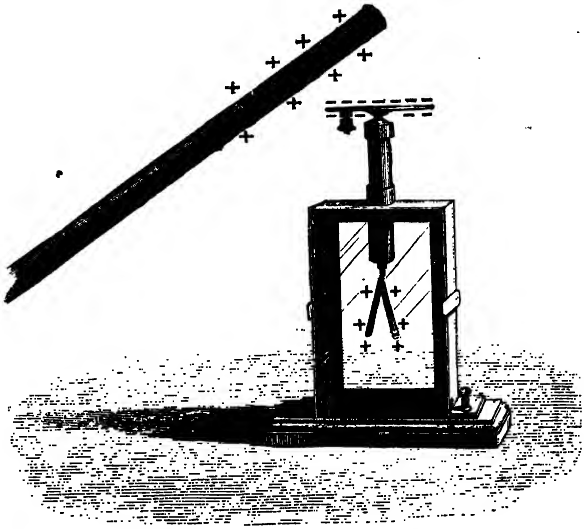


Fig. 10.—Gold-leaf electroscope.

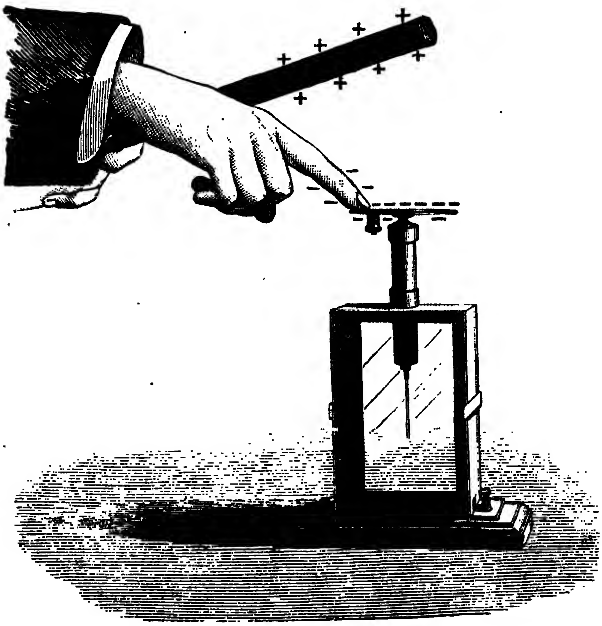


Fig. 11.—Gold-leaf electroscope.

no longer attracted or held in the plate, is free to spread itself out, and some of it passes through the wire to the leaves. They again diverge, but this time are charged with – electricity (Fig. 12). The electroscope is now charged ready for use.

If it be preferred, a negatively charged rod may be presented to the electroscope, the above process will then leave the leaves diverging with a + charge. It should be noticed that gold leaf being extremely thin and light, a very slight charge suffices to cause a considerable divergence.

Use of Electroscope.—To detect, say, a feeble negative charge on the proof plane, bring it near to the plate; a small quantity of the plate's negative electricity is repelled, passes down to the leaves and increases their divergence slightly.

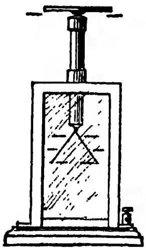


Fig. 12.—Charged electroscope.

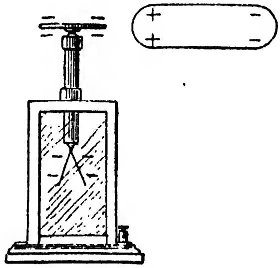


Fig. 13.—Effect of unelectrified body.

On the other hand, a feeble positive charge on the proof plane would attract more – electricity into the plate, repelling at the same time + electricity into the leaves, and thus decreasing their – charge, would cause them to close together slightly. If a body with strong + charge be gradually brought near to the plate, it will first cause the leaves to close together by repelling into them sufficient + electricity to neutralise their – charge; a nearer approach to the plate will drive more + electricity into the leaves, and they having now a + charge will again diverge. Hence we see that in testing the electrification of a body, we ought to bring it cautiously up to the electroscope and be guided by the effect which it first has upon the leaves.

If an unelectrified body of more than one or two inches dimensions be brought near to the instrument, the leaves will close together slightly for the following reason. The unelectrified body has (as explained on p. 664) large supplies of + and − electricity which, being equal, neutralise one another. However, on bringing one end near to the − plate of the electroscope the body is electrified by Induction, so that some of its − electricity is repelled to the far end, and some of its + electricity attracted to the near end. This induced + electricity reacts on the electroscope, attracting a little more of its − electricity from the leaves into the plate, and hence causing the leaves to close slightly.

This effect might be erroneously attributed to a feeble + charge on the body; hence, in doubtful cases it is better when testing for a + charge to have the leaves positively charged, and when testing for a − charge to have the leaves negatively charged, so that in either case we should look for an increased opening of the leaves.

If it be asked, 'Why have the instrument charged at all?' we answer, 'Because a change in the amount of divergence is detected much more easily than the first slight movement'; also when flat together the leaves may stick slightly and so fail to move at all when acted on by a very minute charge.

In order to make the electroscope retain its charge for any length of time the instrument must be thoroughly well dried, and since a film of moisture readily forms on glass it is well to have the top of the glass covered with shellac varnish, which is not so liable to a deposit of moisture. Also the air within the electroscope should be kept dry by placing in it a shallow trough of sulphuric acid, which is very hygroscopic (see HEAT, p. 345).

All Bodies can be Electrified.—With the aid of the Gold-Leaf Electroscope we can prove that almost all pairs of bodies are electrified when rubbed together, one becoming negatively the other positively charged.

At first sight it appears that metals and other conducting bodies are not thus electrified, and the reason of this illusion is obvious, viz. any electricity which is produced on them, imme-

diately escapes to the earth if the conductor be handled during an experiment in the same way as we handle the glass rod, sealing-wax, etc.

If, however, a brass rod be stuck into an insulating glass handle, the rod, on being rubbed or flipped briskly with dry silk, becomes electrified. Sometimes this experiment fails owing to the handle insulating imperfectly; a sure way of showing the electrification of brass, is to flip with a piece of silk the brass plate of an electroscope (previously uncharged). If the instrument be quite dry a few strokes suffice to cause a wide divergence of the leaves.

Electrical Series.—Substances may be arranged in lists—sometimes called 'electrical series'—such that any body in the list is positively electrified when rubbed by one which comes after it, and negatively electrified if rubbed by one which comes earlier. Much, however, depends on the particular specimen of the substance used, hence there is a noticeable difference between the following lists, which have been given by different authorities.

Fur	*Fur*	*Catskin*
Wool	*Glass*	Flannel
Ivory	Wool	*Glass*
Glass	Feathers	*Silk*
Silk	Wood	The Hand
Metals	Paper	Wood
Sulphur	*Silk*	*Metals*
India-rubber	*Shellac*	India-rubber
Gutta-percha	Roughened Glass	*Resin*
Collodion		*Sulphur*
		Gutta-percha
		Gun-cotton

Ebonite is a preparation of india-rubber and sulphur, and being more convenient for lecture-room use than sealing-wax, is often referred to as the negatively electrified body.

CHAPTER II

Distribution of Charge

The Electrophorus—Charge Resides on Surface—Distribution on the Surface—Discharge from Points.

The Electrophorus. — This is an apparatus giving us in succession as many charges of electricity as we please from a surface which needs only one initial excitation by friction. This in itself is a great convenience, but the electrophorus is also of extreme importance because, while affording a useful exercise on induction, the study of its action helps us to understand the working of modern electrical machines such as the Wimshurst.

The electrophorus consists of a thin cake, say 3 mm. ($\frac{1}{8}$ inch) thick, of some resinous material—shellac, sealing wax, etc.—cast in a shallow metal dish called the *sole*: on the resinous cake there lies a disc of brass or another metal, this disc is called the *cover*, and is furnished with an insulating glass or ebonite handle; the cover should be slightly less than the sole in diameter.

Often a small brass knob is fixed by a short stem on the top of the cover. The cake is electrified (negatively) by rubbing with flannel or striking briskly with a catskin. The cover is now placed on the sealing-wax cake, and since neither of them can be *absolutely* flat they only come in contact at a limited number of points, the greater part of their surfaces being separated by a minute air gap. At the few points where there is contact, the sealing-wax gives up its – electricity to the cover, but

the – electricity distributed over the rest of its surface is unaffected, being unable to escape along the nonconducting sealing-wax. The cover is acted on inductively by this

Fig. 14.—Electrophorus.

negative electricity and becomes electrified as in Fig. 15, + electricity being attracted to its lower surface and – repelled to its upper surface.

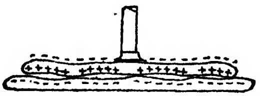


Fig. 15.—Distribution of electricity on electrophorus and cover.

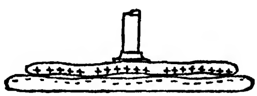


Fig. 16.—Distribution of electricity after touching the cover.

The cover is now touched by the finger, and the repelled electricity escapes through the body to the earth (Fig. 16).

Finally the cover is lifted by the insulating handle (care being taken to take hold quite at the end); the + electricity being no longer attracted to the under surface is free to distribute itself

over both surfaces, and we have the cover charged with + electricity.

The cover when charged will powerfully affect the gold-leaf electroscope and charged balls, etc.

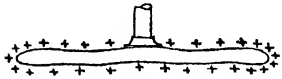


Fig. 17.
Distribution on cover when lifted off electrophorus.

If the knuckle be presented to the knob, the charge escapes from it to the hand just before the knob is actually touched; a slight tingling prick is felt—the forerunner of the more powerful 'shocks' we shall have to describe later—a faint but decided 'crack' is heard and a spark is seen between the knob and handle.

Charge Resides on Surface.—Since electricity—whatever it may be—of either kind repels electricity of its own kind, we might expect that a charge given to a conductor would spread itself out so that each portion should be as far as possible from the remainder; hence we should expect to find the greater part of the electricity on or near the outer surface, and little or none inside. The following experiments show that the charge resides entirely on the surface (or at any rate does not penetrate more than say a hundredth of an inch).

(1) Two equal insulated spheres, one solid and the other hollow, are placed in contact and a charge is given to either of them. We find that the charge is shared equally between them, for when separated they have an equal effect on the electroscope; whereas, if the electricity permeated throughout the material we should expect the solid sphere to take the lion's share.

(2) An insulated hollow sphere has an opening just large enough to allow the disc of the proof plane to pass in and out without touching the edges. If the sphere be charged, the proof plane after touching the outer surface affects the electroscope as usual, but after being passed through the opening and touching the interior surface of the sphere, no effect whatever is produced.

(3) A basket made of wire netting is placed on an insulating stand, as in Fig. 18: a charge of electricity being given to the basket, the proof plane again shows that, notwithstanding the

gaps caused by the meshes, no electricity remains inside the basket. The glass insulating stand shown in the figure is a convenient form, it contains strong sulphuric acid, which keeps the central upright stem dry.

(4) A metal sphere is suspended by an insulating thread and charged; two thin hollow hemispheres of slightly greater radius and fitted with glass handles are now brought together so as to

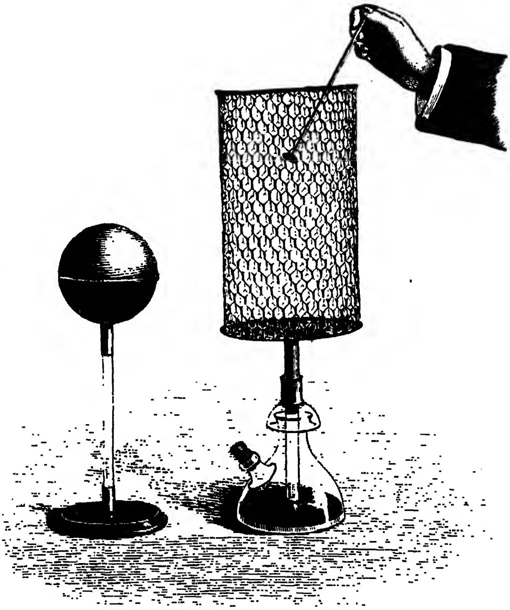


Fig. 18.—Hollow sphere and wire basket, both on insulating stands.

completely enclose the sphere. If not allowed to touch the sphere, the hemispheres can be removed uncharged and the sphere retains its charge; if, however, the hemispheres when together touch the sphere, we find after removing them that the sphere is completely discharged, all the electricity having passed to the outer shell. Care must be taken not to let the hemispheres touch the sphere while being removed.

An interesting illustration of this principle is often to be found in a paper mill. The newly made paper being damp is passed between several heated rollers to dry it, which electrifies it feebly; but as the continuous strip is wound into an immense roll, and the electricity of each turn passes to the outside as soon as it is covered by another fold, the surface of the roll soon becomes powerfully electrified by the accumulated charges; brilliant sparks, and even severe shocks are obtained if the knuckle be presented to the paper. The writer has watched with amusement the pained surprise of an inquisitive terrier who ventured to sniff at the roll.

Distribution on the Surface.—When a sphere is charged we should expect the electricity to distribute itself *uniformly* over the surface, and the proof plane easily shows that it does so.

If, however, a knob A project from a sphere B, the surface of the knob is further removed from all parts of B than the dotted line C which it has replaced, hence we would expect that more electricity, in proportion to its area, would be repelled to A than had previously occupied C.

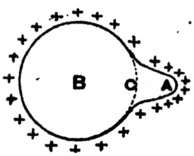


Fig. 19.
Electricity concentrated on prominence.

The proof plane justifies our expectation, being more strongly charged after being applied to A than after application to other points on the sphere. Similarly, on any conductor we find electricity to be accumulated on the more prominent parts of the surface and almost absent from any depressed parts.

We use the term *electric surface-density* to express the intensity of accumulation of electricity at any part of the surface. Hence the surface-density is greatest at all points, edges, or corners.

Electric surface-density at any point is the number of units of electricity (p. 700) per sq. centimetre at the point.

Discharge from Points.—We have seen that owing to its self-repulsion electricity leaves the interior of a conductor and distributes itself on the surface; the same repulsion makes it endeavour to disperse itself more widely still. This is prevented

by the fact that the surrounding air (or it may be glass, petroleum, etc.) is a non-conductor; the air is thus put in a state of electrical strain, or as it is expressed 'electrical tension.' Whenever the surface density is sufficiently increased—either by giving a very strong charge to a conductor of moderate curvature, or a moderate charge to a conductor with points or parts sharply curved—the tension becomes too great for the air to withstand, it gives way

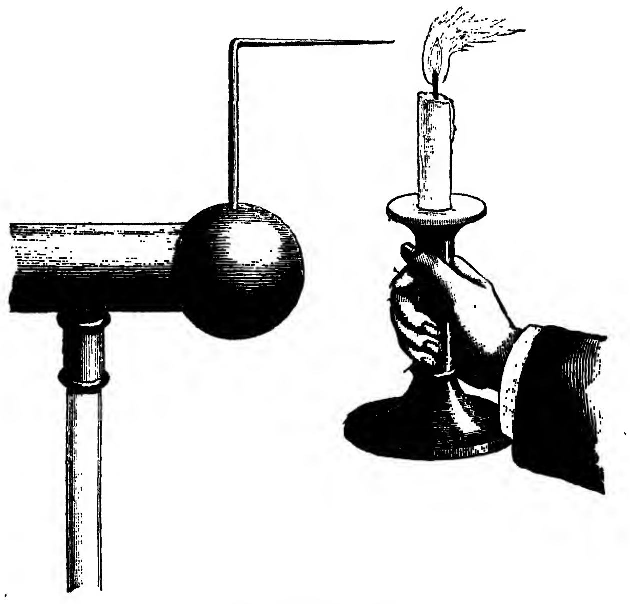


Fig. 20.—Electric wind.

and a 'disruptive discharge' takes place accompanied by a smart crack and a spark.

From a sharp point on a charged conductor electricity escapes continuously with a hissing sound, and in a dark room a faint glow is visible round the point. If there be no other conductor near the point for the electricity to escape to, it will charge even the air itself near the point; the charged air is then repelled from the point and streaming away forms a 'wind' easily perceptible

to the hand, and sufficient in the case of a powerful electrical machine to blow the flame of a candle on one side (Fig. 20).

In order to avoid loss of electricity by silent discharge, any conductor intended to retain a charge for a considerable time should be free from sharp angles or points.

CHAPTER III

Electrical Machines

Plate Electrical Machine—Electric Whirl—Wimshurst Electrical Machine—Explanation of Wimshurst Machine—Discovery of Leyden Jar—Principle of Leyden Jar—Leyden Jar—Electric Hail—Electric Chimes.

We will now proceed to describe machines for readily producing a supply of electricity: the earliest machine was invented about 1640 by Otto von Guericke (who also invented the air-pump). It merely consisted of a big ball of sulphur cast on an axle; one man turned the axle while another man pressed his hands on the ball, which was thus electrified by friction: a chain hanging against the ball carried off the electricity to a 'conductor.'

Newton used a glass globe instead of sulphur, while Hawksbee, Ramsden, Winter, and others, in the course of time, made various improvements. The true *frictional* electrical machine is now almost entirely superseded by induction machines, in which only a slight amount of friction is necessary to produce an initial charge and the subsequent supply is obtained by induction, as in the Electrophorus. We will, therefore, only describe the Plate Frictional Machine.

Plate Electrical Machine.—A circular plate P, of say 50 cm. (20 inches) diameter, is mounted firmly on an axis and can be turned by the handle. At the top and bottom of the plate are pairs of cushioned rubbers R between which the plate passes. The rubbers are made of silk or leather tacked on to wooden blocks and stuffed with horse-hair; usually a bolt passes through

each pair so that by adjusting a nut we can vary the pressure on the glass. A brass conductor C stands on insulating glass columns G; it is often provided with fantastic knobs, rings, and branches whose main use is apparently to add to the mystery which always attaches to anything electrical; but an essential part of the conductor is the pair of 'combs' B*b*, which

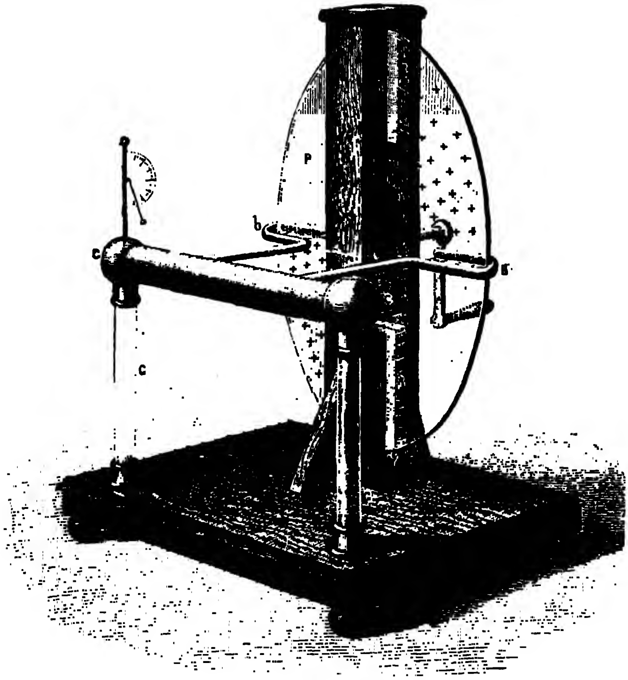


Fig. 21.—Plate machine.

are formed by brass rods bent round the edge of the plate and fitted with a number of points or needles directed towards the plate.

If the plate be turned in the direction LBY*b* the parts of the glass L to B and Y to *b* which have just left the rubbers are charged on both sides with + electricity, as in Fig. 21: as the

charged parts pass between the combs they act inductively on the conductor, repelling + electricity into the remote parts and attracting – electricity into the points. Now we have seen that electricity readily escapes from points, hence this attracted – electricity makes its way from the combs to the plate and there neutralises the + electricity immediately under the points: the parts of the plate passing from comb to rubber (*b* to L and B to Y) are therefore unelectrified and ready to be again excited by the friction of the rubbers.

The continued rotation of the plate brings fresh supplies of + electricity to be neutralised by the withdrawal of more and more – electricity from the combs, the conductor C thereby

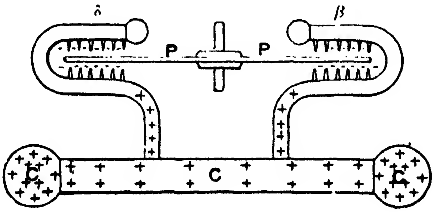


Fig. 22.—Plan of combs and plate.

having a greater and greater deficiency of – electricity is charged more and more powerfully with + electricity (see p. 665).

Electric Whirl.—The whirl consists of five or six brass wires radiating from a central cap which can be balanced on the top of a pivot. The wires have their ends sharply pointed and bent to point in the same way round a circle. When the pivot is connected with the electrical machine, electricity makes its way to the points of the wires, and there escapes into the air (see p. 675). The electrified air is repelled from the points; but by Newton's third law there must be an equal reaction on the

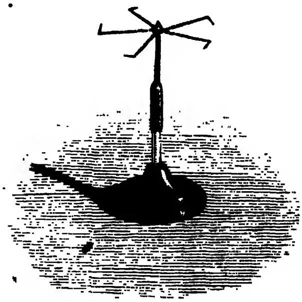


Fig. 23.—Electric whirl.

points, they are therefore driven backwards, and so long as the machine is working well the whirl spins rapidly. Notice that

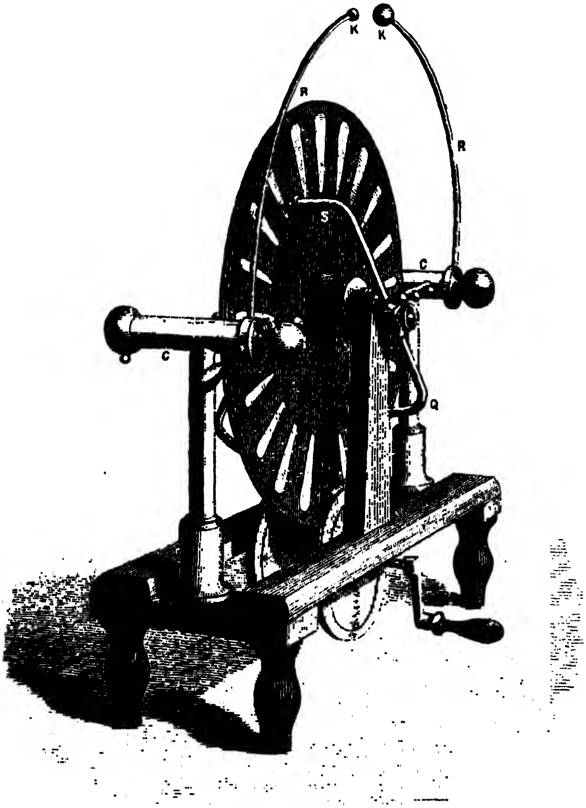


Fig. 24.—Wimshurst machine.

the mechanical action is the same as in Barker's Mill and Hero's Steam Engine.

A very pretty proof of the actual electrification of the repelled air is shown by covering the whirl with a bell jar. After a few minutes all the air in the jar becomes electrified as strongly as the whirl itself, hence further escape of electricity from the whirl is prevented, and the whirl comes to rest.

Wimshurst Electrical Machine.—This is the simplest and most perfect of the machines working by induction. It consists of two circular glass plates, about 50 cm. (20 inches) diameter in a medium-sized machine, mounted on a substantial frame. The plates are driven by bands so arranged that they rotate in opposite directions with the smallest possible clearance between them.

On the outer face of each plate are stuck an even number of strips of thin brass or tinfoil (called Sectors) of shape shown in Fig. 24: the spaces between the strips, as also the rest of the surface of the plates, are well varnished to prevent electricity from leaking over the surface.

At each end of the horizontal diameter of the plates is placed a brass 'conductor' C, with branches D and E on either side of the pair of plates; these are furnished on the inner side with a comb or row of points directed towards the plates.

The conductors are supported on and insulated by the upright columns made of glass or ebonite. To each conductor there is attached a discharging rod R, ending in a knob K, and turning on a pivot so that the knobs can be placed in contact or separated by any desired distance: insulating handles H (Fig. 27) are provided to enable this adjustment to be made while the machine is working.

A conducting rod SQ with a small brush of brassfoil at each end is fixed at an angle of 45° with the vertical, with its brushes lightly touching on the front plate; and a similar rod XY at right angles to the first has brushes touching the back plate.

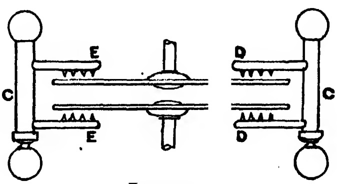


Fig. 25.
Plan of plates, combs, and conductors.

The feeble trace of electrification remaining from the last time of use suffices, as a rule, when a few turns are given to the machine, to work up to a powerful electrification. Occasionally, however, it is necessary

to place an electrified ebonite rod for an instant at the back of the plate behind S. We will base our explanation of the machine's action on this method of excitation.

Explanation of Wimshurst Machine.—The – electrified rod being near the sector at a on the back plate will act inductively on it, endeavouring to repel – electricity out of it and to attract + into it, but a being insulated little effect is produced in it. A similar attempt is made to electrify inductively the sector at β on the front plate, and with more success, for it is at the instant in contact with the brush S; the repelled – electricity can therefore escape along the rod SQ and pass by the brush Q on to the sector γ, while + electricity being attracted passes from the rod SQ on to β.

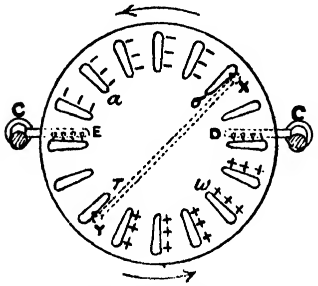


Fig. 26.—Back plate as viewed from front (front plate and SQ having been removed).

The plate being turned in the direction of the arrows, the sectors at β and γ pass on, carrying with them their + and – charges; and the next pair of sectors of front plate coming in contact with S and Q are in a similar manner charged, one with + the other with – electricity.

When the front plate has made a quarter turn, the sectors which were at β and γ have moved to the positions λ μ. They are now near the sectors σ τ of the back plate, which are in contact with the brushes X, Y of the back rod, and acting inductively on the rod they attract – electricity into and repel + electricity from the sector σ, thus charging it negatively and *vice versa* charging τ positively. These sectors will pass on from σ and τ in the direction of the arrows, and reaching the position $a\omega$ after a quarter of a turn will be able to continue the inductive action on the front rod SQ which had been initiated by the electrified ebonite.

It is easy to see that after about half a turn the sectors of

each plate are electrified as in Figs. 26 and 27: those sectors which are approaching the right-hand comb D (on front plate coming round from the top, and on back plate round from the bottom) have a + charge; which on reaching the comb is neutralised by attracting a sufficient quantity of − electricity from the points: hence the conductor CD, from which each passing sector draws − electricity *viâ* the comb, soon becomes strongly charged positively. In a similar manner CE acquires a powerful − charge.

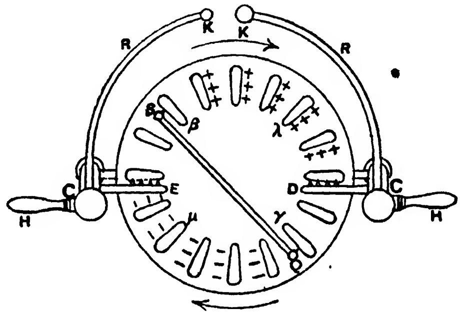


Fig. 27.—Front plate.

The only point left to explain is how the sectors work up in a few turns from a very feeble initial charge to a very powerful electrification. Notice, then, that after the first turn not only is the sector *α* of the back plate charged with − electricity, but also the sectors on each side of it have − charges: the action of the − sector to right of (above) *α* is neutralised by that of the + sector to right of (above) *β*; but the − sector to left of *α* has an uncharged sector opposite to it on the front plate, hence it is able to act inductively on the sector *β* and cause on it a stronger charge than would have been produced by *α* alone.

A similar argument applies to the action at Q, X, and Y, thus each sector on passing a brush receives a slightly greater charge than that on the sector which excites it: the charges, therefore, grow stronger and stronger and the machine soon attains its maximum electrification. The increase does not go on without limit, for it is impossible to prevent leakage from the sectors and the plates, and at a certain point the increased leakage will balance the increase of electrification.

If the machine be worked in the dark, a beautiful glow is

seen on the plates caused by the leakage over their surface, and at all the points of the combs little brushes of delicate violet light are seen, caused by the electrified air streaming from them. A series of brilliant sparks pass between the knobs KK even when 4 or 5 inches apart. A gigantic machine made for the Birmingham Electrical Exhibition in 1887 gave sparks 12 inches long.

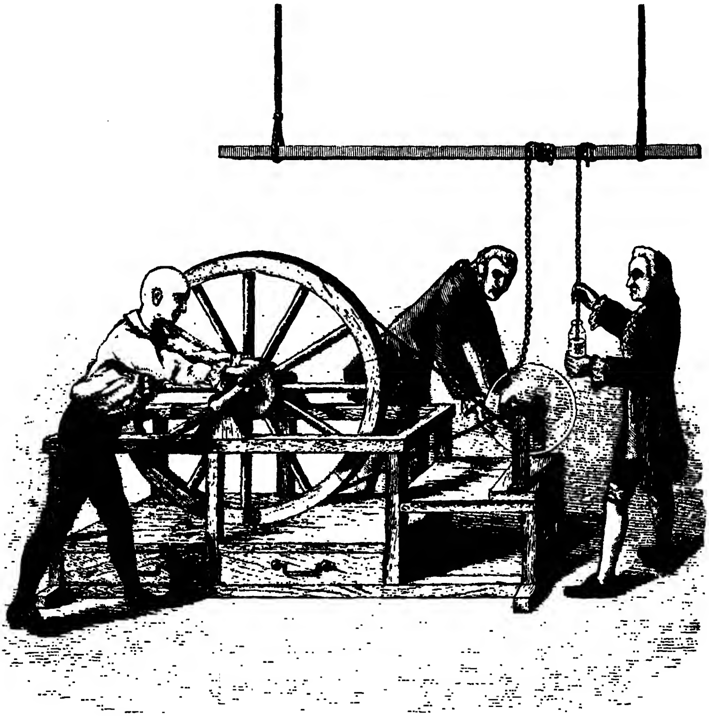


Fig. 28.—Discovery of Leyden jar.

Discovery of the Leyden Jar.—In 1746 (twenty years after the death of Newton) Cuneus, a student at Leyden in Holland, wishing to electrify water, took in his hand a glass flask half filled with water, and let dip into the water the end of a chain hanging from the conductor of a 'glass-globe' machine. Some

time having been allowed to get the water well charged, he attempted to lift the chain from the flask, and received a violent shock in the arms and chest, which caused him to drop the flask, and from the effects of which he took two days to recover. Writing to Réaumur on the subject, Cuneus said he 'would not, for the crown of France, expose himself to a second such shock.'

This discovery caused great excitement in the scientific world, and when the student considers that this was the first electric shock ever experienced—unrecognised lightning strokes excepted—he will see that the amazement was justified. Improvements were soon made, resulting in the Leyden jar (named after the place of the first discovery), which we will describe in the following article.

Principle of Leyden Jar.—In order to lead up to the explanation of the action of the Leyden jar, we will consider the following experiments.

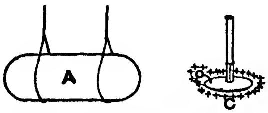


Fig. 29.—Conductor uncharged

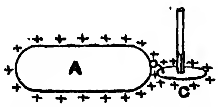


Fig. 30.—Charge shared by conductor and cover.

(1) Let us electrify a large insulated conductor A by giving it a succession of + charges, say sparks from the electrophorus. On first making contact between the charged electrophorus cover and the uncharged conductor, the + electricity of the cover distributes itself in fair proportion between conductor and cover somewhat as shown in Figs. 29 and 30. Thus the cover on removal retains a slight charge, while the greater part remains on the conductor, though attenuated by being spread over so large a surface.

When the cover after recharging is again brought up to the conductor, the + electricity on the latter repels the + electricity of the cover, and resists its passage into the conductor although too feeble to entirely prevent it. Thus the second charge is shared between the conductor and the cover, and each is electrified about twice as strongly as after the first spark.

be $10q$, $100q$, or $1000q$. [Students with sufficient knowledge of algebra will see that these results are obtained by 'summing to infinity' the geometrical progressions $1 + {\cdot}9 + {\cdot}9^2 + {\cdot}9^3 + \text{etc.}$: $1 + {\cdot}99 + {\cdot}99^2 + {\cdot}99^3 + \text{etc.}$: $1 + {\cdot}999 + {\cdot}999^2 + {\cdot}999^3 + \text{etc.}$]

Hence the above arrangement enables us to collect on a given plate, and from the same electric supply, a charge say 1000 times as great as when the plate stands alone. It has a much greater

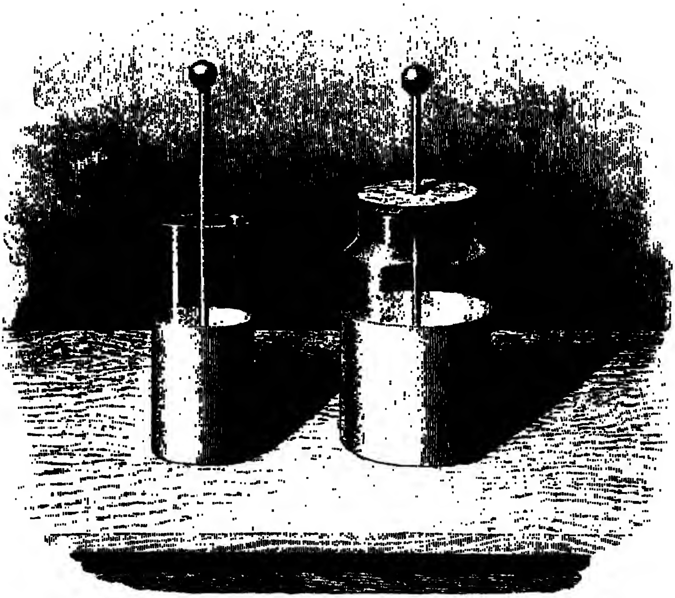


Fig. 34.—Leyden Jars.

'capacity' for electricity than the single plate has. The appropriate name Accumulator has been given to the apparatus, but unfortunately has now fallen into disuse, owing to its having been for several years misapplied to secondary batteries. The name Condenser is now used, but care must be taken not to picture electricity as condensed in any such way as steam condenses into water.

Leyden Jar.—The Leyden jar itself is a thin glass jar coated

about half-way up both inside and outside with tinfoil. Its two coatings correspond to the plates or conductors A and B of the last article; it is an accumulator or condenser of great capacity.

A brass rod terminated by a knob stands up from the centre of the inner coating. In some forms (the more usual) the rod is passed through a wooden cap or lid, and from its lower end hangs a piece of chain which makes contact with the inner coating. The cap has the advantage of keeping out the dust, but it offers a path from the rod to the top of the glass; any leakage of electricity in the open form has to pass up the surface of the glass on the inside and down the outer surface, therefore its insulation is twice as good as that of the common form. In Cuneus' original experiment the water behaved as the inner coating and the hand as the outer coating of the jar.

DISCHARGER. — To avoid receiving severe shocks, the Leyden jar should be discharged by means of a discharger.

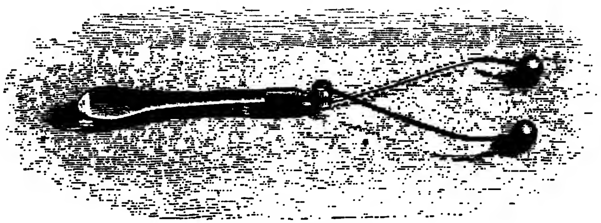


Fig. 35.—Discharger.

This consists of a pair of brass rods, fitted with knobs at one end, jointed together at the other, and mounted on a glass handle. We may discharge a jar by placing one knob in contact with the outer coating, and then bringing the other knob up to the knob of the jar.

We will in this chapter describe a few experiments with the Electrical Machine and with Leyden Jars, some of them being inserted merely for amusement, others because they introduce us to various *effects* produced by electricity in addition to the mere attraction and repulsion which we have already studied.

Electric Hail.—A glass shade stands over a metal plate on

which lie a number of pith balls; through the top of the shade passes a brass rod carrying a second brass plate. The base plate is connected to one conductor of the machine and the upper plate to the other (light brass chains with hooks at the end are convenient for making such connections). As soon as the machine is worked, the base plate and the balls lying on it become, say,

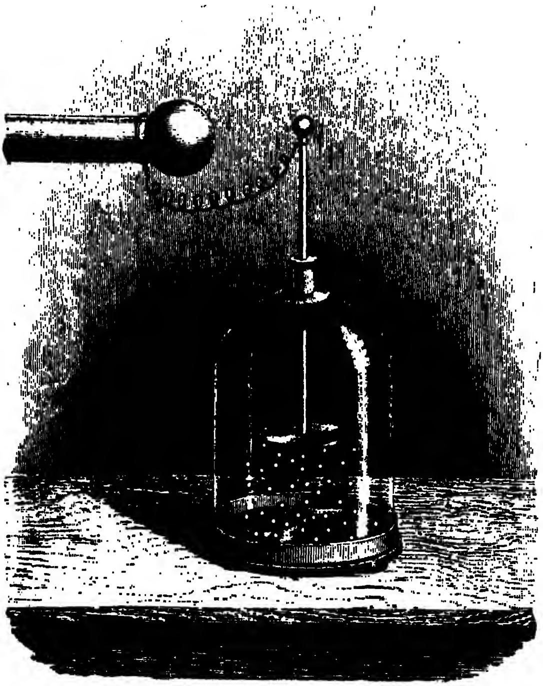


Fig. 36.—Electric hail.

negatively charged and the upper plate positively. The balls are therefore repelled by the lower and attracted by the upper plate. They jump briskly upwards, and striking the plate give up to it their – charge and receive a + charge. They are then repelled downwards, and on striking the base plate again jump up to the top plate, so that a continual bombardment of the balls takes place between the plates. The name Electric Hail

has been given because of a suggestion made by Volta that hailstones may thus move up and down between two clouds oppositely charged.

There is a similar experiment in which a doll made of pith dances up and down in a ludicrous manner between two plates connected with the machine as before.

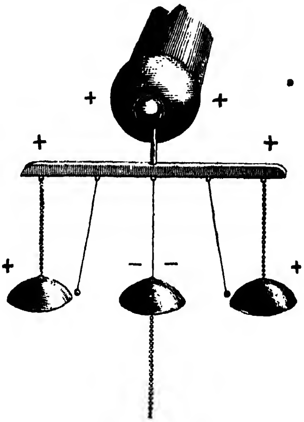


Fig. 37.—Electric chimes.

The Electric Chimes.—Three bells are hung from a metallic cross-bar which is connected with one of the conductors (say +) of an electrical machine. The middle bell is suspended by a silk thread, and therefore insulated from the cross-bar; a chain hangs from it to the ground or to the − conductor of the machine. Two small balls are suspended by silk

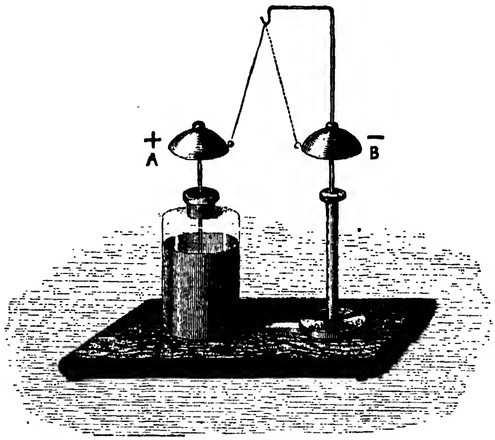


Fig. 38.—Slow discharge of Leyden Jar.

threads between the bells. They are first attracted to the outer bells, then repelled to the inner one, and so keep up a continual ringing so long as the cross-bar is electrified.

This pretty experiment was devised by Franklin during his work on thunder-storms for the useful purpose of calling attention when any action was taking place in his apparatus.

A similar arrangement can be fitted to a Leyden jar which is slowly discharged by the ball carrying a small + charge from A to B, and − charge from B to A at each swing to and fro (see Fig. 38).

CHAPTER IV

Electrical Effects

Shocks—Sparks—Heating Effects—Chemical Effects—Magnetic Effects.

Shocks.—We have described the shock experienced by a single individual; the shock may be felt simultaneously by any number of people provided they join hands so as to make a continuous chain; the man at one end must hold the jar by its outer coating while the man at the other end touches the knob. In some French experiments made during the excitement which followed the discovery of the Leyden jar, a severe shock was thus given to a regiment of 1500 soldiers.

We may here mention the shocks given by Voltaic Batteries, Ruhmkorff Induction Coils, and Dynamos, although these instruments are not described until later on. No shock whatever is felt when we touch the terminals or wires connected with the terminals of a battery containing two or three cells; if the number of cells be increased say to ten, a slight pricking sensation is felt when a wire from a terminal is held very lightly in each hand; the effect is more evident if the hands be previously soaked with water containing a little acid, it is then accompanied by a slight twitching of the muscles; these sensations become much more marked as the number of cells is increased to 40 or 50, and are felt to a similar extent with a low pressure dynamo—say one giving a difference of potential of 50 to 100 volts. A nasty shock is given by 100 to 150 cells or 200 to 300 volts, and anything above this is distinctly dangerous. A

shock from a dynamo working at 600 to 1000 volts is, as a rule, fatal, even if given by a momentary accidental contact with an uninsulated wire. The danger arising from the enormous potentials, ten or twenty thousand volts, often employed in large electric lighting stations, is very great and the utmost caution has to be observed in their use.

Sparks.—If the knobs of the Wimshurst machine be separated by a short distance, say half an inch or less, the spark usually consists of only a single bright line of light, which on examination shows at the negative knob a very brilliant point separated by a stretch of fainter purplish violet light from a longer brilliant line which extends to the positive knob.

If the distance be increased to 2 inches (5 cm.) or more the discharge breaks up into a number of sparks similar to the last, side by side and slightly bowed outwards, as though they repelled one another.

The spark from the Leyden jar is much brighter, stouter, and gives a sharper sound than the direct spark between the knobs of the machine; this is of course due to the greater quantity of electricity which passes.

If the conductors of a Wimshurst machine be connected with the inner coats of two Leyden jars, the outer coats of which are connected together, then a spark only passes between the knobs when each jar is fully charged, it therefore has all the characteristics of a Leyden jar spark.

We saw (p. 675) that the air round an electrified body is strained by the electricity, and when the strain at any point becomes too great, a passage for the electricity is torn through the air and the whole charge rushes through. The sound of the spark is probably due to the tearing asunder and subsequent closing together of the air. Heat is produced by this sudden rush, hence the spark is able to ignite spirits or gunpowder, and to produce an explosion in a mixture of oxygen and hydrogen. Thus in the experiment represented in Fig. 39 a small brass cannon — usually known as *Volta's Cannon* — has a somewhat large chamber at the breech end instead of being of uniform

bore; it can thus hold a fairly large volume of any explosive mixture of gases, say, coal gas and air: a cork is inserted firmly in the muzzle, a plug of ebonite is screwed firmly into the breech, and through the ebonite passes a brass wire terminated by a small knob at each end, as shown by the sectional drawing at the top of the figure. The lower knob is fixed very near to

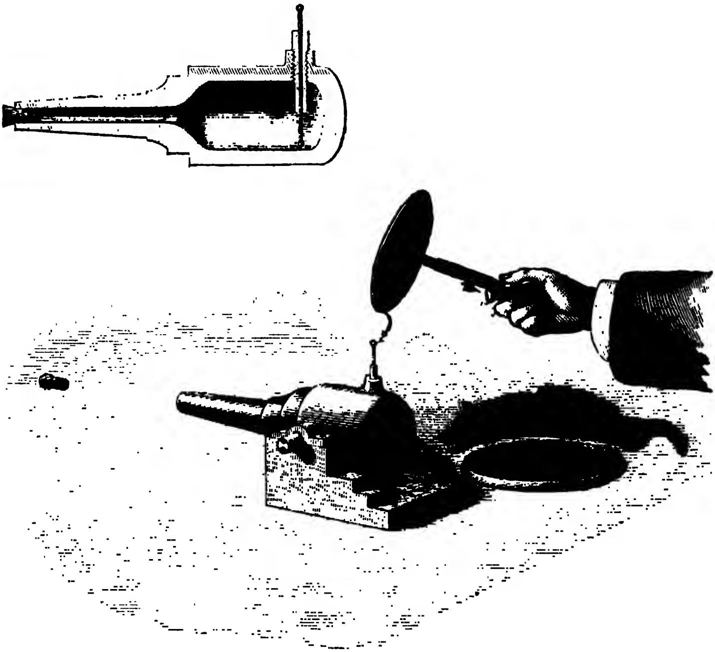


Fig. 39.—Volta's cannon.

the inner surface of the chamber; when a spark from the Electrophorus cover is passed to the upper knob, a spark passes simultaneously inside the cannon across the gap below the lower knob; this ignites the explosive mixture, and the cork is projected with great violence. The object of the ebonite plug is to insulate the brass wire and so prevent the spark from passing to the outside of the cannon. Again, if we insulate ourselves by

standing on a sheet of india-rubber, we can light the gas by a spark from the knuckle; to do this take hold of one of the conductors of a Wimshurst machine with one hand and present a knuckle of the other hand to the gas burner; when the machine is worked, sparks pass from the knuckle to the burner and readily ignite the gas.

It may seem strange to beginners that any strain can exist in so mobile a substance as air; but it must be remembered that although ordinary matter passes easily through air and therefore cannot cause strain in it, the passage of electricity (whatever it

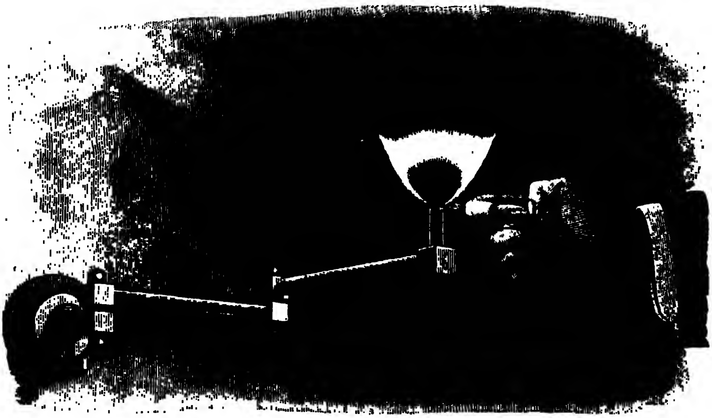


Fig. 40.—Gas lighted by knuckle.

may be) is opposed in air just as much as, say, the passage of ordinary matter through glass.

Electricity causes strain in other insulating materials, and the strain amounts to an actual rupture or piercing, if a spark pass through the material.

When the collectors of the Wimshurst are connected with Leyden jars, the spark between the knobs will each time puncture a card placed between them; the hole usually has a slight burr on each side as though it were burst outward from the middle. A sheet of glass may be pierced by the spark, but unless it be very thin, such as one of the slips used to cover the

specimen on a microscopic slide, a powerful spark from a battery of Leyden jars (see p. 688) is necessary. Precautions have to be taken to prevent the spark leaping round the edge of the glass instead of through it.

Heating Effects.—A fine wire placed in the path of the electricity, when a spark is taken from a battery of Leyden jars, is heated and becomes red hot, white hot, or even melts according to its fineness.

A piece of gold leaf placed in the circuit is raised to a high temperature owing to its extreme thinness, and it is not merely melted but volatilised, *i.e.* converted into vapour. Franklin took rough copies of portraits and other patterns by this means; a pattern is pricked or cut through a thin card, on the ends of

Fig. 41.—Picture produced by volatilising gold leaf.

which are stuck strips of tinfoil T (Fig. 41); a strip of gold leaf reaches from T to T across the card: underneath the card is a strip of paper. The card, paper, and gold leaf are held firmly together in a screw press and the discharge from a Leyden jar is passed through the leaf; the vapour passes through the slits of the card and, condensing on the paper at the back, forms an outline copy of the picture.

Chemical Effects.—Two platinum wires are fixed in two fine glass tubes so that only the points show through the ends of the tubes. The wires are thus insulated by their glass covering, so that electricity can only pass to or from them at the points. The tubes are placed opposite each other in water (Fig. 42), and when the upper ends of the wires are connected to the conductors of a Wimshurst machine, electricity passes from one to

the other through the water when the machine is worked. As the electricity passes, minute bubbles of gas are seen to form at the points, these, if collected, would prove on examination to be oxygen and hydrogen—hence *electricity in passing through the water has decomposed it.* Further, + electricity passes from A to B, leaving the liquid at B; hydrogen also leaves the liquid at B; − electricity passes from B to A, leaving the liquid at A; oxygen also leaves the liquid at A, so that **hydrogen appears to travel with + electricity and oxygen with − electricity.**

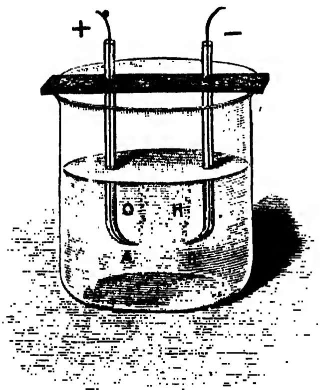


Fig. 42.—Decomposition of water.

If crystals of sulphate of copper ($CuSO_4$, blue vitriol) be dissolved in the water we find that, on working the machine, a thin coating of copper is deposited on the platinum at B, while free acid is formed round A. This shows that the copper sulphate

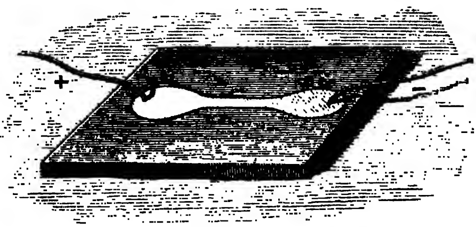


Fig. 43.—Decomposition of potassium sulphate.

is decomposed into copper and sulphuric acid; also that **the metal appears to travel with the + electricity and the acid appears to travel with the − electricity.**

Many chemicals are similarly decomposed when electricity passes through them; we will only give one further instance—an experiment due to Faraday. Two small circles of blotting

paper with a connecting strip are soaked with sulphate of potassium and coloured with litmus. The litmus on B is made slightly acid, which gives it a red tinge, and that on A slightly alkaline, which gives it a blue tinge; platinum wires connect A and B with the machine. When + electricity passes from A to B and − from B to A, a blue spot is formed round the end of B wire and a red one round the end of A wire, showing that the salt having been decomposed into acid, and alkali containing the metal, the acid has travelled with − electricity to A while the metal has travelled with + electricity to B and there formed an alkali.

Note that in the first of the experiments hydrogen behaves in the same way as metals do in the second and third.

Magnetic Effects.—If a piece of insulated copper wire (*i.e.* wire covered with gutta-percha, silk, or other non-conducting material) be coiled into a spiral and a Leyden jar discharged through it, we find that a sewing needle or small steel bar placed inside the coil is magnetised by the passage of the electricity round it.

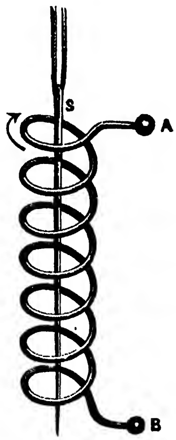


Fig. 44.—Needle magnetised by discharge of Leyden jar.

If the + electricity pass from A to B and − from B to A, then, if on looking at the end A, the + electricity pass round the coil 'anti-clockwise,' a N. pole is formed in the needle at the end near A. If on looking at A the + electricity passes round the coil 'clockwise,' as in Fig. 44, a S. pole is formed near A.

CHAPTER V

Quantity of Electricity: Potential

Law of Attraction and Repulsion — Measurement of Electricity — Electric Potential — Potential of a Conductor — Analogy to Level of Water — Potential of Earth Zero—Electrometer.

Law of Attraction and Repulsion.—Hitherto we have merely said that 'like electricities repel, unlike electricities attract' without any reference to the magnitude of the attracting or repelling force. Coulomb proved with the help of his torsion balance, which we will not describe here, that the force between two small electrified bodies varies inversely as the square of the distance between them, *i.e.* the law of attraction is the same for electricity, for magnetism, and for gravitation. For example, if the repulsion between two balls at a distance 5 cm. be 27 dynes, then at a distance 15 cm. (3 times as great) the force will be 3 dynes ($\frac{1}{9}$ of 27 dynes). Moreover, the force is proportional to the quantity of electricity on each ball, thus, if we increase the quantity on one ball 4 times and that on the other 7 times, the force is multiplied by 28, *i.e.* 4 times 7.

Measurement of Electricity.—Just as we need a unit or standard length (the foot or the centimetre) and a unit or standard quantity of matter (the pound or the gramme), so we need a unit or standard quantity of electricity, in terms of which we can measure all other quantities; the following unit has been chosen.

The Electrostatic Unit of Electricity *is the quantity*

which, placed on a minute body at a distance one centimetre from another minute body carrying an equal quantity of electricity, repels it with a force one dyne.

[It is necessary to say a 'minute body,' for in bodies of appreciable size the electricity, being distributed over their surfaces, will at some points be more and at others less than a centimetre apart.]

The following examples will make the law of attraction clear.

Ex. 1. 1 unit at distance 1 cm. from 1 unit causes force 1 dyne,

$\therefore$ 1 unit ,, 11 cm. ,, 1 unit ,, ,, $\frac{1}{11^2}=\frac{1}{121}$ dyne,

7 units ,, 11 cm. ,, 13 units ,, ,, $\frac{7\times 13}{121}=\frac{91}{121}$ dyne.

Ex. 2. So if q units be at a distance d cm. from q' units the force $=\frac{qq'}{d^2}$ dynes.

Ex. 3. What equal amounts of electricity must be placed one foot apart in order that the repulsion may be equal to a force of 1 lb.-weight?

Let x be the number of units on each body: then since 1 ft. $=30\cdot5$ cm., force of repulsion $=\frac{x\times x}{(30\cdot5)^2}$ dynes.

Also 1 lb.-weight $=454$ grammes-weight $=454\times 981$ dynes,

$$\therefore \frac{x^2}{(30\cdot5)^2}=454\times 981, \quad \therefore x=30\cdot5\times\sqrt{454\times 981}$$

$$=20{,}400 \text{ units of electricity.}$$

Electric Potential.—A body A with a + charge repels any other positively charged body P, hence if we carry P near to A we have to overcome the repulsion which resists us, that is, we have to do work; and the nearer we bring P to A the more work we have to do. When P is at a considerable distance—say 100 feet or more—the repulsion is as a rule negligible, hence beyond some such range no work is done in moving P about. However, to guard against inaccuracy when dealing with very large bodies, say electrified clouds, we speak, in the following definition, of bringing a body up from infinity, in spite of it being a somewhat inaccessible starting-point.

The ELECTRIC POTENTIAL *at any point is the work which has to be done against electric forces in bringing a + unit of electricity from infinity to that point.*

Hence the nearer we are to a positively charged body the greater will be the potential, and beyond the range of say a hundred feet from an electrified body the potential is zero.

If two bodies A and B have + charges it is clear that in bringing our + unit from infinity to P we are opposed by both A and B and have to do work against both repulsions; hence the potential at P is greater when B is present than when A alone is present.

If a third body C with a − charge be near, then its attraction helps us to bring our + unit to P; it does some of the work for us, and we ourselves have *less* work to do; that is, the potential at P is lowered by the presence of a negative charge at C.

It can be proved mathematically that the potential at a distance r from a charge of q units of + electricity is $\frac{q}{r}$; and

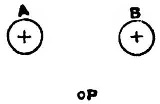


Fig. 45.
Extra positive charge raises potential.

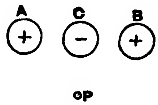


Fig. 46.
Extra negative charge lowers potential.

that the potential at a point P in the presence of several charged bodies is the sum of the potentials due to each body separately.

Hence, if + charges q_1, q_2, q_3 be at distances r_1, r_2, r_3 from P,
and − charges q_4, q_5, q_6 be at distances r_4, r_5, r_6 from P,

$$\text{potential at P} = \frac{q_1}{r_1} + \frac{q_2}{r_2} + \frac{q_3}{r_3} - \frac{q_4}{r_4} - \frac{q_5}{r_5} - \frac{q_6}{r_6}.$$

Just as the electric forces oppose us when moving a positively charged body from a place of low to one of higher potential, so they help us by doing work in the reverse movement; that is, the electric forces themselves tend to cause + electricity, or a positively electrified body, to move from a place of high to one of lower potential: moreover, since − electricity is attracted where + is repelled, it follows that − electricity, or a negatively electrified body, tends to move from a place of low to one of high potential.

Potential of a Conductor. — Since electricity can move readily in a conductor, we see that, if the potential were different at any two points in a conductor, + electricity would immediately flow one way and – the other until the potential was equalised. Hence, *the potential is the same at all points in or on a conductor* (provided the electricity be at rest).

If a conductor be charged gradually by bringing up to it unit after unit of electricity, the opposition to the approach of each unit increases as the charge on the conductor increases; hence the work to be done in imparting each successive unit to the conductor increases; that is, the *potential* of the conductor *rises.*

The POTENTIAL OF A CONDUCTOR *is measured by estimating, in ergs per electric unit, the work which would have to be done, against the electric forces, to bring up from infinity to the conductor a very small charge of positive electricity.*

Analogy between Level of Water and Potential of Electricity.—We have seen already that, although electricity is in all probability not a fluid, still it resembles one in many respects; in comparing electricity with water we find a resemblance between 'level' and 'potential.' Thus, in lifting water from a low level to a high level we have to do work, just as we have in moving + electricity from a place of low potential to one of high potential. Water, or a bucket filled with water, tends to descend from a high level to a low one, just as + electricity, or a body carrying + electricity, tends to move from high to low potential.

If water be poured into a tank it spreads out until the level is everywhere the same, just as electricity given to a conductor spreads out until the potential is everywhere the same.

If a pipe connect a tank at a high level with another at a low level a current of water flows through the pipe; and if a wire connect a 'conductor' at high potential with another at low potential a current of electricity flows along the wire.

The analogy between water and electricity, however, breaks down if pressed too far. Thus, two similar bottles of water *attract* each other (by gravitation), whereas two similar charges of electricity *repel* one another.

A + charge and a – charge on bodies near each other will

neutralise each other's action on a third body; but an empty bottle (or say a bottle of water) does not neutralise the attraction of a full bottle of whisky.

Potential of Earth Zero.—In considering the flow of water we are usually concerned with the *difference* of level or height between one place and another, and to render the estimation of this difference easy it is usual to compare all heights with a standard height or level, namely, 'sea-level': so in estimating electric potentials it is desirable to have a standard potential from which to measure all others; the potential of the earth at any point is a convenient standard, hence, as a rule, the potential of the earth is taken as zero.

The action of the Leyden jar, of the Wimshurst machine, and all the phenomena of induction may be explained by considering the potentials at various points; unfortunately we have not space here for these explanations. We will call attention to the point that, just as a tank or a reservoir of great capacity takes a great quantity of water to raise its level one foot, so a conductor of great capacity takes a great quantity of electricity to raise its potential one 'erg per unit of electricity.' Now, when electricity is derived from a given source, say an electrophorus or a Wimshurst, there is generally a limit to the potential at which it is supplied, just as with a common pump there is a limit to the height through which the water can be lifted. If any conductor be charged as far as possible by the given apparatus, its potential will rise to a limiting value and no further. Hence if the conductor have a great capacity, as a Leyden jar, it will acquire a far greater charge than a body of small capacity would acquire when charged by the same apparatus.

Electrometer.—Electrometers are instruments for measuring the difference between the electric potentials of bodies. We will not fully describe one, but may mention that Lord Kelvin's **Quadrant Electrometer** is one of the most delicate: in it a light flat strip of aluminium is delicately suspended within a round shallow brass box: this box is divided into four separate

pieces by two cuts made along two diameters at right angles to each other. The four pieces are therefore quadrants of a circle: each quadrant is mounted on an insulating glass stem, and alternate quadrants are connected together by wires. When it is wished to compare the potentials of two bodies, one body is connected to one pair of quadrants, the other body to the other pair; the aluminium strip is given a charge of electricity, say a negative charge, and is then attracted towards the pair of quadrants which has the greater positive potential.

CHAPTER VI

Atmospheric Electricity

Franklin's Experiment—Thunder-storms and Hot Weather—Big Rain Drops after Thunder—Photographs of Lightning—Lightning Conductors—Measurements of Atmospheric Electricity—Pyroelectricity—Electric Fishes.

Franklin's Experiment.—The similarity of the jagged lightning flash to the smart spark of the Frictional Machine and of the Leyden jar suggested to the early workers in Electricity that lightning was but a mighty electric spark leaping from one cloud to another or to the earth; they recognised that the 'shock' given by a Leyden jar bore an obvious resemblance to the lightning 'stroke,' and that the snap of the spark was but a peal of thunder produced in miniature.

The great Benjamin Franklin in 1752 carried out at Philadelphia his original suggestion of drawing down electricity from the clouds: he flew a kite near the clouds during a storm and expected electricity to make its way down the string. At the end of the string he slung a key from which to draw the sparks, if any came; and he held the string by means of a silk ribbon in order to insulate it. At first the string was dry and no result was obtained, but as soon as rain fell, the string, being wetted, conducted an abundant supply of electricity to the key, which then yielded powerful sparks.

This class of experiment was extremely dangerous, for occasionally sparks nine feet long were obtained, and in 1753 a Russian physicist, Richmann, was killed by a shock.

Having established the fact that clouds generally *are* electrified, we are confronted with the problem '*how* do they become electrified, electrified indeed to such an enormous potential that they can yield sparks possibly a mile long?' The problem is one which, up to the present, has baffled physicists to solve completely and satisfactorily. Doubtless the electrification is largely due to friction of the wind against the surface of the earth, while another agent may be the continual evaporation of water from the sea, from rivers, and from moist land.

Thunder-storms and Hot Weather.—There is not much accurate knowledge on this subject, hence what follows must only be considered as a series of hints at the truth.

Dry air is one of the best insulators, hence during a long spell of hot dry weather there is little opportunity for electricity to escape from the air to the earth; we might therefore expect that the upper strata of the atmosphere would gradually accumulate the electricity which is continually being produced by friction and evaporation; at the same time remember that although the air may *feel dry* (because it is hot and capable of holding a great quantity of water vapour), yet it is continually drinking up more moisture, a process to which an end must come when, sooner or later, the air becomes nearly saturated. Ultimately some slight fall of temperature causes these upper strata to become moist, the water vapour within them begins to condense into minute particles, and clouds are formed whose conductivity may be fairly good. The electricity which, before the condensation, was distributed throughout the volume of the air, makes its way to the surface of the cloud, and being thus packed more densely together it has a greater tendency to escape in sparks.

Previous to a thunder-storm the clouds are in great commotion, great masses being torn asunder, others uniting together; now these clouds being electrified, some more and some less strongly, act inductively on one another, and if a piece happen to be torn away, while more than its fair share of electricity has been

induced into it, it may soar away intensely electrified. Several such pieces may unite to form a big cloud charged to the enormous potential necessary to produce a flash of lightning.

Big Rain Drops after Thunder.—Lord Rayleigh has proved that drops of water which strike together when slightly electrified tend to run together into big drops, but when unelectrified they generally rebound from one another. The following pretty ex-

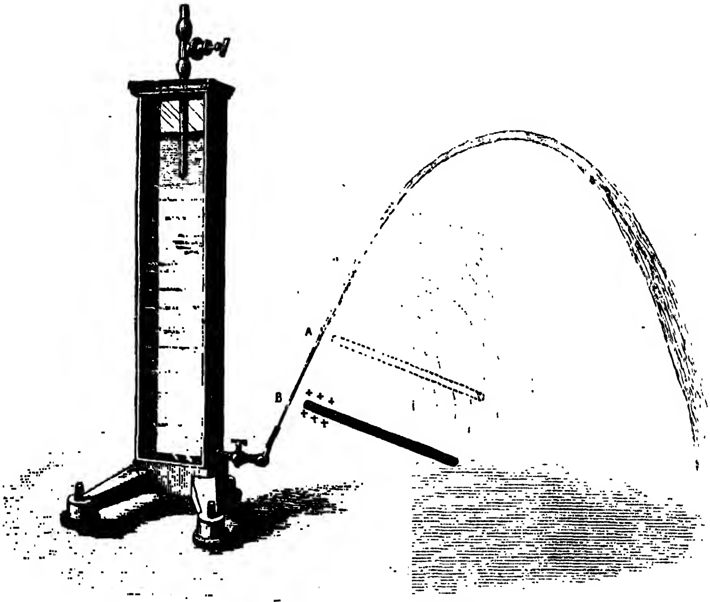


Fig. 47.—Jet of water electrified.

periment illustrates the matter. Water from a tank is allowed to flow in a fine jet from a glass nozzle; it begins to break into drops at a point A about a foot above the nozzle; it rises nearly to the height of the tank, and scatters somewhat even before reaching its highest point. If an electrified glass rod or sealing-wax be brought within a few feet of the jet it immediately pulls itself together and flows in a compact stream of big drops from the point A to the ground; moreover, it rises higher than

before, for it offers less surface to the air and therefore meets with less resistance.

If the electrified rod be brought close to A the drops as they break away are *strongly* electrified, and their mutual repulsion causes them to be scattered in all directions as a fine spray.

Similarly it is possible that just before a big thunder-clap the rain drops are kept apart by strong electrification, but that after the clap the feeble charge remaining causes them to coalesce into big drops.

Photographs of Lightning.—Within the last few years many photographs of lightning flashes have been taken. We reproduce

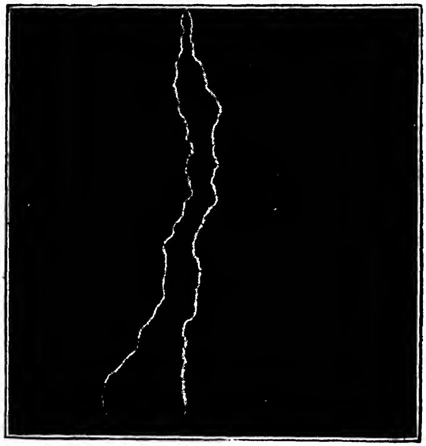


Fig. 48.—Photograph of lightning.

one here, kindly lent by Mr. A. R. Dresser, of Bexley Heath; it shows clearly that the zigzag representation of lightning given in paintings and engravings until recently is quite erroneous.

Lightning Conductors.—When the electricity is endeavouring to make its way from a charged cloud to the earth it naturally follows whatever path offers the least resistance.

Now, although timber and building materials are not good conductors, yet they conduct better than the air, hence the flash

will probably take a path leading it down a tall tree or building, and even these offer so much resistance that they catch fire or are torn to pieces by the shock. Buildings may be protected from lightning by fixing to them one or more stout copper conductors (with a section of say half an inch square) from the highest point down to the ground; the conductor offers so little resistance that the lightning current flows harmlessly through it to the ground. It is imperative that the conductor should make a good connection with the ground, this can be attained by carrying it along underground to a place where the soil is damp, and there connecting it to a big sheet of metal buried in coke; a cheaper plan is to connect it with water-pipes underground, but it is very risky to connect to gas-pipes.

At the upper end the conductor is provided with one or more sharp metal points, gilded to prevent rusting; these were introduced by Franklin, who, indeed, first suggested the use of lightning conductors. The object of the points is to reduce the chance of the building being 'struck' at all: they act as follows: if a cloud strongly charged with + electricity be floating above the building it induces − electricity on the part of the earth immediately below and into the conductor itself; the − electricity attracted into the points very readily escapes from them into the air (see p. 675), and so long as the charged cloud remains overhead there will be a silent stream of negative electricity flowing steadily from the point into the air; thus the electricity of the cloud is gradually neutralised without the passage of a violent spark.

Measurements of Atmospheric Electricity.—Experiment has shown that the air is at all times and seasons in a different electrical condition to the earth below it. At any time the potential of the air is either positive or negative compared with that of the earth, which we selected as zero (p. 704): when we say that the potential of the air is positive we mean that there is a tendency for + electricity to pass from it to the earth (or − electricity from the earth to the air), and *vice versâ* for negative potential. Sir William Thomson's (Lord Kelvin's)

'water-dropper' is the most perfect instrument for finding the potential of the air. A small tank of water is supported on an insulating glass stand. A wire from the tank leads to a pair of quadrants of an electrometer, keeping them at the same potential as the tank: the other pair of quadrants is connected to the earth, and therefore at zero potential.

When the tap is turned on, a stream of fine drops flows from the nozzle at the end of the projecting pipe. So long as the tank is at a different potential from the air surrounding the nozzle, the drops carry off induced electricity from it, and in about a minute the potentials of the air and the water become equal. In Fig. 49 the air is shown as having a negative poten-

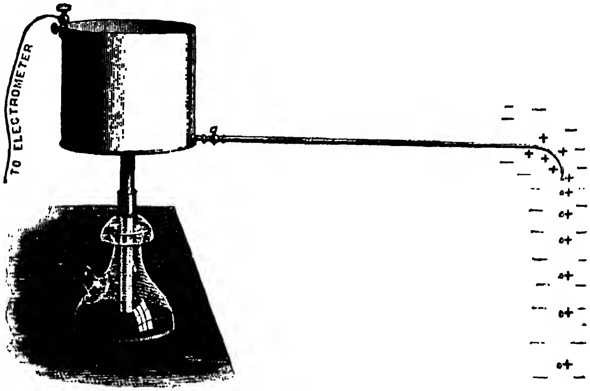


Fig. 49.—Water-dropper.

tial, so that + electricity is being induced into the nozzle and into each drop of water just as it leaves the nozzle; hence each drop of water breaks away carrying a positive charge, and this continual carrying away of + electricity soon brings the tank to the same negative potential as that of the air.

During fine weather the air is almost always at a positive potential; during wet weather it is sometimes positive, sometimes negative; during snow it is almost always positive, and if the wind be high the potential is about twenty-five times the fine

weather potential. During thunder-storms it may be positive or negative, and as much as fifty times the normal potential.

Sir W. Thomson found that as height increases the potential rises also; the rate being from *20 to 50 volts per foot rise.*

Other Sources of Electricity

Pyroelectricity.—This name is given to electricity produced

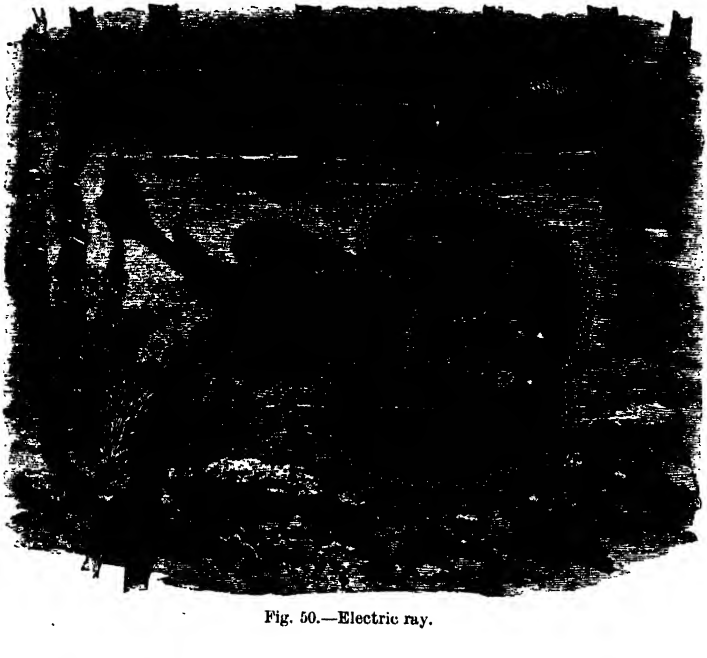


Fig. 50.—Electric ray.

in certain crystals during heating or cooling; the effect is only very slight, and is best shown in tourmaline, which, when heated, becomes positively electrified at one end of the crystal and negatively electrified at the other. A crystal of tourmaline, suspended by a silk thread, can, when heated, be attracted or repelled by other electrified bodies.

Electric Fishes.—Certain fishes are capable of giving powerful

electric shocks, they are provided with special organs which are capable of generating the electricity. The best known of these fish are the *Raia Torpedo* (the electric ray) found in the Mediterranean and in the Nile, and the *Gymnotus Electricus*

Fig. 51.—Electric eel.

(the electric eel) found in South America, which, when grown to a length of 5 or 6 feet, gives a very severe shock which will stun a horse; marvellous descriptions are given by the old geographer Humboldt of contests between horses and electric eels.

VOLTAIC ELECTRICITY

CHAPTER I

Electric Current

Galvani's Experiment—Volta's Experiment—Voltaic Cell—Electric Current—Oerstedt's Experiment—Ampère's Rule—Fleming's Rule—Simple Galvanometer—Resistance—Internal and External Resistance—Polarisation of the Cell.

Galvani's Experiment.—In 1790 Galvani, a professor of anatomy at Bologna, observed curious convulsive movements in the muscles of a recently killed frog when touched at different points by iron and copper which were in contact. These movements, resembling the muscular contractions experienced when a shock is taken from a Leyden jar, naturally suggested the idea that some electrical action was going on; and the fact that Galvani observed similar contractions in dead frogs when affected by ordinary electric machines justified the assumption.

Volta's Experiment.—Volta very soon after proved by means of the 'condensing' electroscope that certainly some electric action occurs when two different metals—say zinc and copper—are placed in contact. The following form of his experiment is best adapted to prove this: a round copper plate (say 1 ft. diameter) is substituted for the usual knob of a gold-leaf electroscope, and a similar zinc plate provided with a handle is placed on it. These plates are varnished so that they do not

come into metallic contact. The zinc plate may be lifted up and replaced without any effect on the leaves. If, however, the zinc and copper have been connected for an instant by a copper wire, as in the figure, we find on lifting the zinc that the gold leaves diverge. A test with an ebonite rod (p. 667) shows that the electroscope is charged negatively.

Voltaic Cell.—Students of chemistry will remember that in order to prepare hydrogen gas, pieces of commercial zinc are placed in dilute sulphuric acid; that the zinc dissolves in the acid, forming sulphate of zinc, while innumerable bubbles of hydrogen are formed on and escape from the zinc. If, however, *pure* zinc

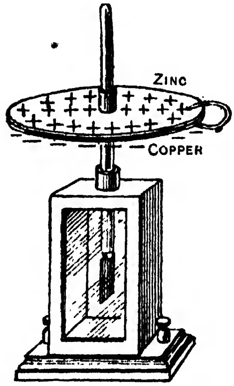


Fig. 52.—Volta's electroscope.

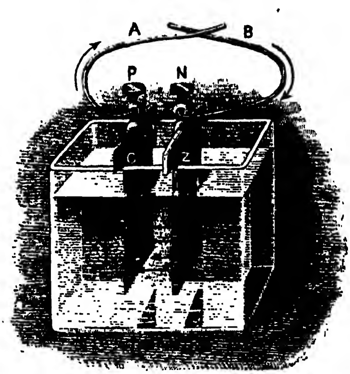


Fig. 53.—Voltaic cell.

be placed in the dilute acid, practically no chemical action takes place—the zinc is not dissolved, hydrogen is not evolved. Copper, whether pure or commercial, is not acted on by sulphuric acid.

Now take a plate of pure zinc and a plate of copper, place them in a glass jar containing dilute sulphuric acid (say ten parts water to one part acid), no chemical action occurs. Attach to each plate a copper wire (either by soldering or by means of a 'binding screw' or 'terminal,' as shown at P and N in Fig. 53). Now press together the ends of the two wires: immediately a vigorous chemical action commences, zinc is dissolved; bubbles

of hydrogen appear on the copper, but none on the zinc. This is an astonishing result. We perhaps need not be surprised that the zinc should dissolve, but it is strange that the hydrogen should appear on the copper instead of on the zinc, as in the former experiment. We are reminded of the experiment (p. 698) in which water being decomposed by the passage of electricity, hydrogen appeared at one platinum point, having travelled with the + electricity, and oxygen appeared at the other point; and judging from what took place in that experiment, we should suspect that the appearance of hydrogen on the copper is caused by + electricity travelling from Z to C through the liquid in the direction of the arrows, and – electricity travelling in the opposite direction. The hydrogen bubbles are generally very minute; they cling to the surface of the copper, and give it a milky-white appearance, and when brushed away they speedily form again, provided the wires are still held together.

If this be so, the + electricity will not accumulate and remain on the copper, nor the – electricity on the zinc, for the copper and zinc are connected by the wire and form a continuous conductor, and each will pass on its electricity to the other *viâ* the wire, so that there will be a continuous flow or current of + electricity from C to Z along the wire, as shown by the arrows, and a current of – electricity in the opposite direction.

The above arrangement is called a *Simple Voltaic Cell*, after Volta, who discovered it. The currents so produced have for many years been called Voltaic Electricity, Galvanic Electricity, or Galvanism (after Galvani), but there is no need to retain the names, as there is no essential difference between this and Frictional Electricity.

Electric Current.—In dealing with batteries and dynamos it is usual to mention only the current of + electricity, to speak of it as *the* current, and of '+ electricity' as 'electricity.' This is merely for convenience of writing and speaking, and although we shall henceforth adopt the custom in this book, we

must be at all times ready to think of the equal – current flowing in the opposite direction.

Instead of uniting the wires A and B directly, we may connect them by means of any wire or metallic body, and we find that whenever there is metallic connection between C and Z, the chemical action, as indicated by the hydrogen bubbles, takes place, and whenever the metallic connection is broken the chemical action ceases, *i.e.* when the circuit is closed (or complete) a current passes; when the circuit is open (or broken) no current passes.

Current is measured in *Ampères* (see p. 772): an incandescent lamp takes about $\frac{1}{2}$ ampère; an arc light takes about 10 ampères.

Since electricity passes along the wire from the terminal P to the terminal N, it follows that P must be maintained at a higher potential than N. P is usually called the *positive terminal* or *positive pole* of the cell, since + electricity starts out of the cell from P; and, conversely, N is the negative terminal or pole.

This difference of potential would rapidly be destroyed by the passing of + electricity along the wire from P to N (and, we must remind the student, by the passage of – electricity from N to P) were there not some compensating action going on in the cell. There must be somewhere a pump-like action forcing electricity through the cell from N to Z, and through the liquid to C and P, lifting it up the electric 'hill' that it may run through the wire down the electric 'slope' from P to N.

In mechanics we define force as 'that which moves or tends to move material bodies;' similarly in electricity we call Electromotive Force that which tends to move electricity. To avoid all possibility of confusing it with mechanical force, it is well both in writing and speaking to designate electromotive force by its initials E.M.F.

The foregoing discussion shows that somewhere in the cell between P and N there is an E.M.F.; and ever since the day when Volta invented his cell there has been much dispute as to

the exact point at which the E.M.F. is situated. Volta himself believed that the E.M.F. occurred at the junction of two dissimilar metals, and that there was little or no E.M.F. where metal and liquid came in contact. The diametrically opposite view is now almost universally accepted, namely, that very little E.M.F. occurs at the junction of two metals; and that considerable E.M.F. may occur at the junction of metal and liquid.

We will not here give the arguments on either side, but will merely state that either hypothesis can be made to explain the FACTS almost equally well. It shall suffice to look on the cell as a whole, to consider it as a sort of electric-circulating pump which tends continually to keep the Positive Pole at a higher potential than the Negative Pole. And just as in a water-circulating pump we might not trouble whether the water-motive force occurred at the junction of water and piston, or at this valve or that valve, but might be content to know that the coal consumed in the furnace is the source of the energy produced (that is, of the work done), so we must be content to know that the zinc consumed in the cell is the source of the electrical energy produced. And further, just as in any engine we must look for the consumption of coal, gas, petroleum, or some fuel to supply the energy, so in any electric cell (some hundreds have been designed) we must look for the consumption of zinc, iron, or some material to supply the energy.

It is convenient to notice here that in almost all cells zinc is employed in company with some other metal or carbon—the cells of the secondary battery being the only exception that we shall describe—and in all of these **the Negative Pole is attached to the Zinc.**

E.M.F. and Difference of Potential are measured in *Volts* (see p. 773): the E.M.F. of a Daniell cell is about 1 volt; of a dynamo from say 100 to 1000 volts; of a Wimshurst machine, 100,000 volts.

Oerstedt's Experiment.—If the wire from the voltaic cell be held just above and parallel to a compass needle which is at rest,

then immediately the circuit is completed the needle is deflected (*i.e.* turned), as in the left of Fig. 54.

Now after letting the needle settle to rest, hold the wire under and parallel to it; on completing the circuit the needle is deflected in the opposite direction, as in the right of Fig. 54.

Reverse the direction of the current either by interchanging the ends of the wires at the terminals or by twisting the wire

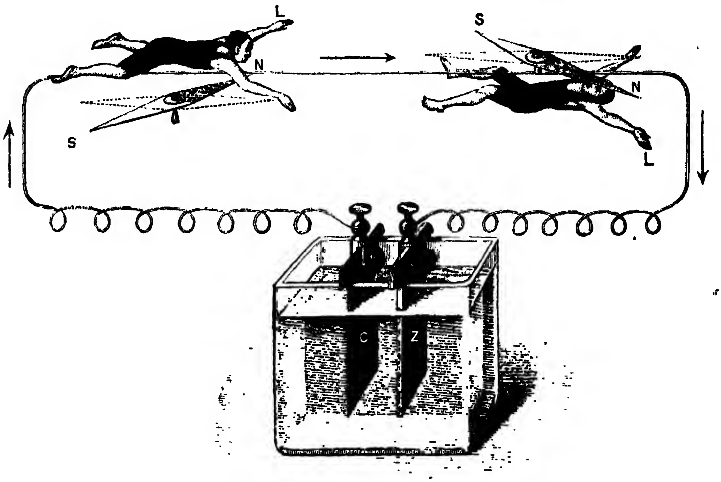


Fig. 54.—Oerstedt's experiment.

round, the direction of deflection of the needle is in each of the above cases reversed.

This effect of the current on a magnetic needle is of extreme importance, and its discovery by Oerstedt, a professor of Copenhagen, in 1820, marks a new era of electrical science; for on it and its developments by Ampère and Faraday depends the working of all modern practical inventions, from telegraph and telephone to dynamo and motor.

A precise knowledge of the direction in which the needle is deflected is so useful that we give three distinct methods of remembering it.

I. **Ampère's Rule.**—Think of the current as a stream of

water flowing along a pipe; picture a man (or doll) (Fig. 54) swimming forward with the stream; let him always face the needle, swimming on his back, or either side if necessary, then the NORTH POLE of the needle is driven towards his LEFT. The South Pole is driven with equal force in the opposite direction; hence the needle as a whole is acted on by a couple (*i.e.* a pair of equal and opposite forces).

II. **Fleming's Rule.**—Clench the right hand, then open out

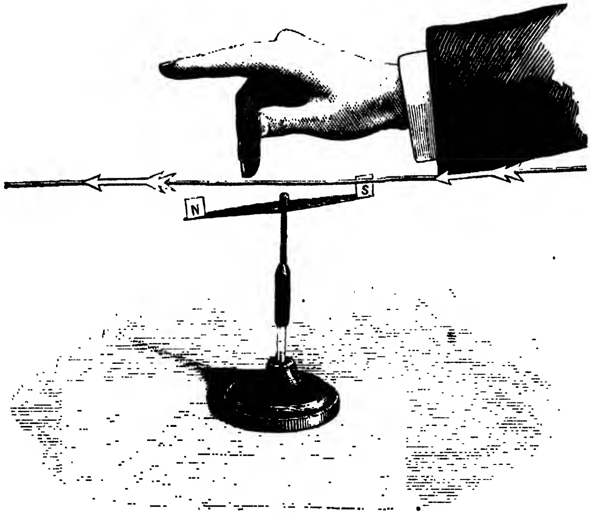


Fig. 55.—Fleming's rule.

the thumb and first two fingers, as in Fig. 55, making them as nearly as possible at right angles to each other. Then place the hand so that the forefinger (index) points along the wire in the direction in which the current is flowing, and so that the second finger points to the needle, then the thumb points in the direction in which the N. pole of the needle is driven. This rule is a modification of one given by Professor Fleming.

III. Think of a common corkscrew encircling the wire. Twist or untwist the corkscrew so that it may travel along the

wire in the same direction as the current; then the N. pole of the needle is urged round the wire the same way as the point of the corkscrew moves.

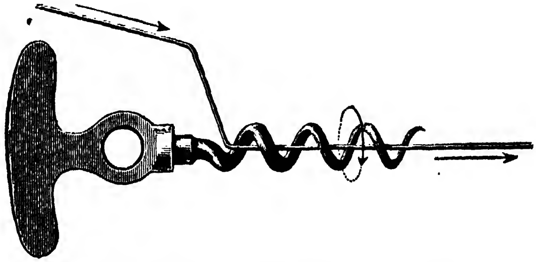


Fig. 56.—Screw movement of north pole and current.

Simple Galvanometer.—Bend a piece of stout copper wire into a rectangular shape as ABCD, and connect with the wires

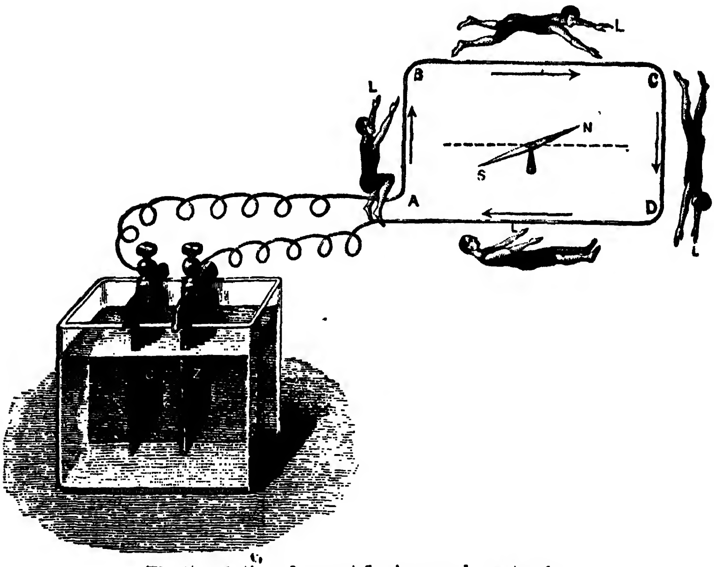


Fig. 57.—Action of current flowing round a rectangle.

from a simple voltaic cell; suspend a magnet needle in the middle, then the dolls as sketched show that all four sides, AB,

BC, CD, DA, of the rectangle urge the N. pole in the same direction (*viz.* away from us in the picture): hence we have a greater couple acting on the needle than when the current merely flows along a straight wire above or below it. Now instead of taking one turn of wire, take several, as in Fig. 58, the current has to pass round each turn in succession, and each turn having an almost equal effect, we get a further increase in the couple acting on the needle. Thus if there be five turns the couple will be about five times as great as for a single turn. If a graduated circle be placed under the needle, we can estimate roughly the amount of the current by noting through how many degrees the needle has turned, hence the arrangement described

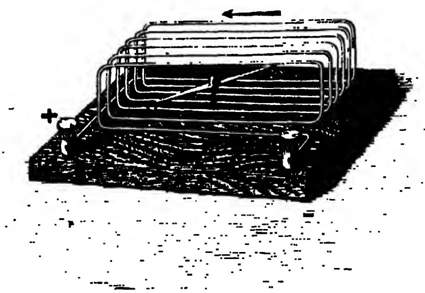


Fig. 58.—Simple galvanometer.

constitutes a rough Galvanometer (*i.e.* measurer of Galvanism, if we use the original name for the electric current).

Notice that a current, however great, cannot do more than turn the needle through 90°, hence the current is not proportional to the deflection. For example, it would take about seven times as much current to deflect 80° as to deflect 40° (not twice as much); however, up to about 30°, the deflection is roughly proportional to the current.

Later we will describe more refined galvanometers.

Resistance.—If a long wire be inserted in the circuit—say between the copper and A in Fig. 57—the current having to pass through this extra length of metal is, as seems natural, diminished, and in consequence the galvanometer deflection is

diminished also. The longer the wire is and the finer it is, the greater is the falling off in the current. Hence it seems that bodies offer a passive *resistance* to the passage of the current through them. The resistance has some resemblance to the frictional resistance offered to the movement of ordinary matter, for we shall see later on that wires are heated by the passage of the current. The resistance also depends on the material of the wire; thus, iron resists six times as much as copper, and lead twelve times as much as copper. It may help the student to again picture the current as a stream of water flowing through a pipe. If one end of the pipe be at a given difference of level, say fifty feet, above the other (corresponding to the given difference of potential between the terminals of the cell), then a short pipe will allow a greater flow of water than a long one will; and a pipe of small diameter will allow a less flow than a wide pipe.

Resistance is measured in *Ohms* (see p. 772). The resistance of an average electric bell is about 15 ohms; resistance of an Atlantic cable about 10,000 ohms.

Internal and External Resistance.—The whole path described by the current—the cell, the terminals, the wires, and any instruments through which the current passes—is called the circuit. The *external* circuit is the part of the circuit which lies outside the cell (*i.e.* everything between the terminals): its resistance is the *external resistance.*

The current having to pass through the materials within the cell itself meets with resistance within it: this is the *internal resistance.*

Polarisation of the Cell.—If clean zinc and copper plates—the latter free from hydrogen—be placed in the cell, and the wires from the terminals be connected to our rough galvanometer, we at first get a big deflection, nearly 90° in all probability; but, as the hydrogen bubbles begin to form more thickly on the copper, the deflection decreases rapidly, and in a few minutes becomes inappreciable; the dwindling of the deflection of course indicates a corresponding dwindling of the current. If we get rid of the hydrogen from the copper plate by brushing it with a

feather, or by lifting it from the cell and wiping it, the current is at once restored to its original intensity. This proves conclusively that the hydrogen is the cause of the currents falling off. The cell in its enfeebled condition is said to be **Polarised.** The polarisation results from two separate causes: (1) we have seen that air is a non-conductor of electricity; the same is true of hydrogen and most gases, hence when the copper is covered with a film of hydrogen bubbles, electricity has more difficulty in finding its way through the cell; that is, the passive *resistance* of the cell is increased. (2) The hydrogen film also actively opposes the passage of the current, and tends to drive it back; that is, it exerts a 'back E.M.F.' (electromotive force). This is easily proved as follows. When the cell is thoroughly polarised, quickly remove the zinc plate and replace it by a clean copper plate. We find that the galvanometer needle is deflected in the reverse direction, the angle turned through being almost equal to the original deflection; the hydrogen gradually disappears from the first copper plate, and the current continues until all the hydrogen has gone.

Notice how, in the last experiment, we have a current produced *without any contact of dissimilar metals*; hence such a contact is certainly not the only source of an E.M.F.

CHAPTER II

Voltaic Cells

Batteries—Series—Parallel—Advantage of each Method—Bichromate Cell—Daniell Cell—Grove Cell—Bunsen Cell—Leclanché Cell—Amalgamating Zinc.

If either the copper or zinc of the voltaic cell (or both of them) be replaced by another metal we find, as a rule, that a current is produced; that the E.M.F. is greatest when one plate is much more easily oxidisable than the other; and that the negative pole is always that attached to the more oxidisable plate. We will in this chapter describe a few of the principal varieties of cell, the chief object in their design being to overcome polarisation and to reduce internal resistance.

Batteries.—In order to increase the current or to increase the E.M.F., several cells may be used connected together: we then call them an Electric Battery. There are two principal methods of connecting the cells—

(1) **In Series.**—The zinc of each cell is connected to the copper of the next, as in Fig. 59; the odd zinc at one end carries the negative pole of the battery, and the odd copper at the other carries the positive pole. This arrangement gives a greater E.M.F. than the single cell; for example, it is easily seen that 7 cells give seven times the E.M.F. of a single cell, for all the cells push in the same direction one behind the other. The rise of E.M.F. from 0 to 4 volts is shown in Fig. 59.

But since the whole current has to pass through each cell in

succession it meets with seven times as much resistance; that is, the '*internal resistance*' of the battery is seven times the internal resistance of a single cell.

(2) **In Parallel.**—All the zincs are connected together and to the negative terminal: all the coppers are connected together and to the positive terminal. Hence all the zincs are at the same potential and all the coppers at the same potential, and we only have the same E.M.F. as for a single cell; but on the other hand, only a fraction of the current of the external circuit has to pass through each cell: thus if there be 7 cells, $\frac{1}{7}$ of the current passes through each cell, hence the '*internal resistance*' of the battery is only $\frac{1}{7}$ the resistance of a single cell.

Advantage of Each Method.—The current in the circuit depends not on the external resistance alone, but on the sum of

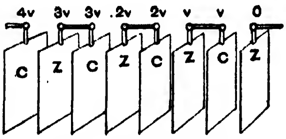


Fig. 59.—Cells in series.

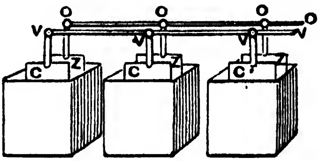


Fig. 60.—Cells in parallel.

the internal and external resistances; hence when the external resistance is high, say 100 ohms or more, it makes little difference whether 1 ohm or 7 ohms be added as internal resistance, but an increase of E.M.F. would greatly increase the current; therefore with high external resistance we use the cells 'in Series.'

If the external resistance be low, say 1 ohm or less, then it makes a great difference whether we add $\frac{1}{7}$ ohm, 1 ohm, or 7 ohms internal resistance, far more than would be compensated for by the increased E.M.F. of the battery in series; therefore with low external resistance we use cells 'in Parallel.'

A combination of the two methods is often used in connecting up the cells of a battery; they are put 'part in series, part in parallel.' To obtain the greatest possible current the resistance of the battery should, if possible, be made equal to the external resistance.

Bichromate Cell.—In this cell the copper plate is replaced by carbon—a very hard form called retort-carbon is used, it is formed in the retorts of gas-works, and can be sawn into plates and rods. In the dilute sulphuric acid are dissolved crystals of bichromate of potash ($K_2Cr_2O_7$), a convenient proportion for the liquid being 20 parts water, 2 parts bichromate, 1 part acid.

This cell was invented by Poggendorf; in it polarisation is prevented by the powerful oxidising action of the solution. Bichromate of potash—as the chemical formula shows—contains an excessive proportion of oxygen, which seizes on the hydrogen at the carbon plate before there is time to form a polarising film of bubbles.

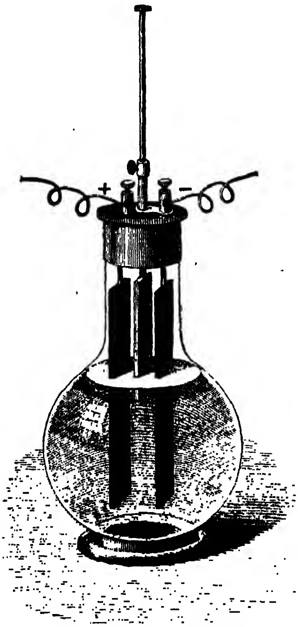


Fig. 61.—Bichromate cell.

Bichromate batteries made in bottle form are very convenient for amateurs making occasional experiments. Usually they have two carbon plates connected at the top and placed one on each side of the zinc, thus reducing internal resistance: the zinc plate is fixed to a rod so that it can be drawn out of the liquid and not be acted upon when the cell is out of use.

E.M.F., 1·8 to 2·3 volts.

Internal Resistance for cells of ordinary sizes, ·3 to ·7 ohm.

Daniell Cell.—The metals used are zinc and copper, as in the simple Voltaic Cell: in the variety which we describe the copper is formed into a tall jar and contains a saturated solution of copper sulphate (blue vitriol $CuSO_4$); within this is placed a porous (*i.e.* unglazed) pot containing a zinc plate immersed in dilute sulphuric acid. The object of the porous pot is to keep the two liquids from mixing, for if any copper sulphate makes

its way to the zinc plate it immediately acts on it, precipitating metallic copper and dissolving the zinc wastefully to form zinc sulphate.

When the circuit is closed, the sulphuric acid in the porous pot acts on the zinc and forms zinc sulphate; the hydrogen from the acid travels through the cell with the current to the porous pot, and there meeting with the copper sulphate it exchanges places with the copper; hydrogen sulphate (*i.e.* sulphuric acid H_2SO_4) is formed and copper set free, the latter continues the journey with the current and is deposited on the

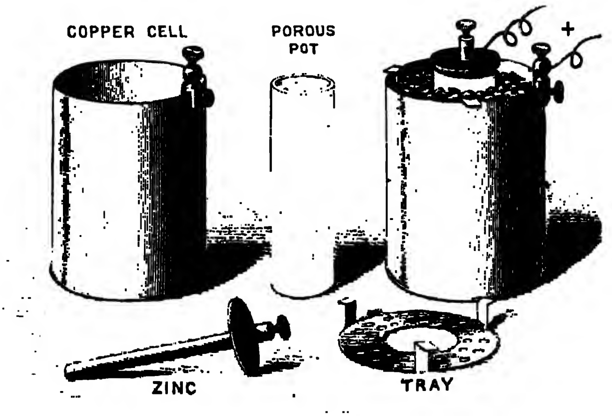


Fig. 62.—Daniell cell.

outer copper cell. Hence instead of polarising bubbles being formed on the copper, its thickness is increased by the deposited copper.

A copper ring is placed inside the top of the cell and forms a tray in which are put crystals of copper sulphate: these dissolve in the solution and keep it saturated during the working of the cell.

Batteries of Daniell cells are very useful for heavy telegraph work, and in all cases where a current is wanted continuously: they can be worked for hours without any practical falling off of E.M.F. In both Leclanché and Daniell cells the current has

to pass through a porous pot, hence the internal resistance is higher than in the bichromate cell.

E.M.F., from 1 volt to 1·1 volt. Internal Resistance for cells of ordinary sizes ·5 to 1 ohm.

Grove Cell.—The metals used are zinc and platinum. An outer glazed cell A contains dilute sulphuric acid, in which is immersed the zinc C cast in the shape shown in Fig. 63, so as to lap round both sides of a flat inner porous cell B: the latter

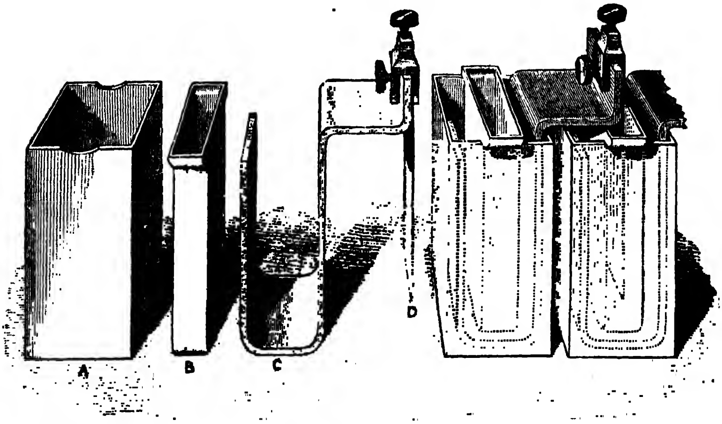


Fig. 63.—Grove cell.

contains strong nitric acid in which the platinum plate D is immersed.

Nitric acid (HNO_3) is a powerful oxidising agent; it prevents the formation of a polarising film of hydrogen bubbles on the platinum, since its surplus oxygen combines with the hydrogen to form water; at the same time it gives off pungent red fumes of nitrogen trioxide (N_2O_3), which partly dissolve in the nitric acid, giving it a murky blue colour. Grove cells are invaluable for laboratory use, since their internal resistance is low and E.M.F. high; a battery of five or six Groves will maintain a big current for two or three hours without any appreciable falling off. The main objection is their first cost, platinum being now as valuable as gold (copper cannot be used, as it would be

immediately attacked and destroyed by the acid); the objectionable fumes which eat into any metal near the battery are a further disadvantage.

E.M.F., 1·9 volt. Internal Resistance, ·15 to ·25 ohm.

Bunsen Cell.—Bunsen, to reduce the first cost of the cell, used a carbon rod in place of the platinum plate; the cell is not quite so convenient as the Grove cell. The usual form of Bunsen cell is shown in Fig. 64.

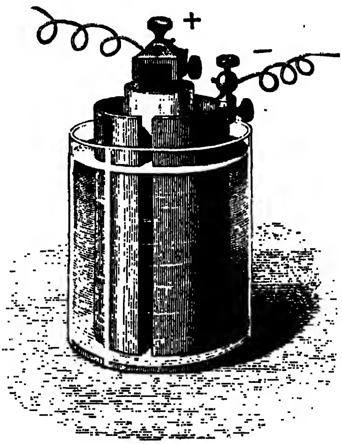


Fig. 64.—Bunsen cell.

E.M.F., 1·95 volt.

Leclanché Cell.—The copper is again replaced by a carbon plate: the liquid used is a solution of salammoniac (ammonium chloride NH_4Cl) with no free acid. The absence of acid is an immediate advantage, for the zinc does not dissolve when the current is not passing, hence the battery may be left standing for any length of time without removing the zinc. In one form of the cell the carbon plate is placed in a porous (*i.e.* unglazed) earthenware pot and packed in with a pounded mass of carbon and black oxide of Manganese (MnO_2): in other cells black oxide and pounded carbon are mixed together and converted into solid blocks, which are grouped round the carbon plate (Fig. 65).

In the Navy pattern, the porous pot is replaced by a bag of 'fearnought,' which is a thick felt.

Polarisation is prevented by the power of absorbing gases possessed by carbon. The hydrogen set free by the current, instead of forming bubbles, is absorbed by the carbon. There is of course a limit to the absorbent capacity of carbon; hence if the current be allowed to flow continuously for more than a few minutes, the carbon gets saturated, bubbles are formed, the cell

is polarised, and the current dies away. If the cell be now left for some time with 'open' circuit, it gradually recovers its strength, since the excess oxygen in the black oxide is able to combine slowly with the dissolved hydrogen.

Leclanché batteries are very useful for working electric bells, telephones, and branch telegraph lines. They are used in the Navy for firing submarine mines, etc. Their length of life depends on good treatment, especially good insulation; the writer has had

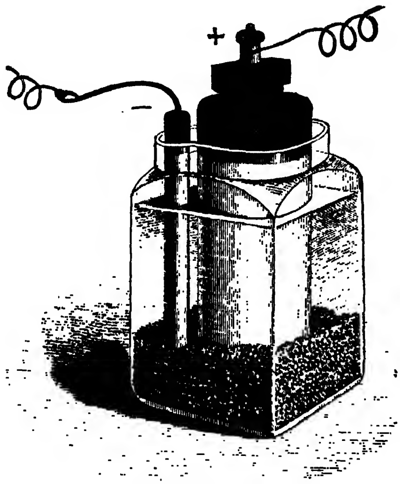


Fig. 65.—Leclanché cell.

a pair of cells working a bell regularly for nine years, the only attention required being the annual addition of a little water.

E.M.F., 1·5 volt. Internal Resistance, ·5 to 2 ohms.

Secondary Batteries.—See p. 744 for description.

Amalgamating Zinc.—At the beginning of Chap. I. we remarked that pure zinc does not dissolve in dilute sulphuric acid, but that commercial zinc is rapidly dissolved. The reason for this is probably as follows: in the commercial zinc any impure particle behaves as though it were a different metal from the purer particles which surround it, but both the impure and the pure particles at the surface of the zinc are in contact with

acid and also are in contact with each other; hence their position resembles that of the copper and pure zinc in a simple Voltaic cell when connected by a very short wire, and a current of electricity flows round the minute circuit which they form. This action goes on at many places on the surface of the zinc, it is called **Local Action,** and causes the zinc to be eaten away at some points more than others, so that its surface becomes pitted all over with small holes.

The expense of preparing chemically pure zinc makes it out of the question to use it in electric batteries, but fortunately it has been found that when the surface of commercial zinc is amalgamated with mercury it behaves in a battery quite as well as pure zinc. To amalgamate zinc it is only necessary first to clean the surface well and then, placing the zinc with a little dilute acid and some mercury in a flat dish, to rub the mercury well into the surface of the zinc with the help of a soft pad. The amalgamated surface is clean and silvery, it consists of a pasty mixture of zinc and mercury, for zinc dissolves in mercury; the protection it affords is probably due to the uniformity of this pasty layer, any particles, say, of iron impurities being insoluble in mercury and rubbed away during amalgamation.

CHAPTER III

PROPERTIES OF THE ELECTRIC CURRENT

Chemical Action—Electrolysis—Decomposition of Water—of Copper Sulphate—Electroplating—Laws of Electrolysis—Table of Electrochemical Equivalents.

Chemical Action.—We have seen that chemical action accompanies the passage of the current through the cell; experiment shows that any liquid is decomposed by the electric current passing through it. An exception must be made in the case of chemical elements such as mercury and other molten metals—not being compound they cannot be 'decompounded.' Some liquids, such as turpentine and petroleum, are non-conductors, and we need not answer the Dundreary-like question, 'What would happen if they did conduct?'

Electrolysis.—Faraday, to whom our knowledge of this branch of electricity is mainly due, gave the name *electrolysis* (λύσις, *lusis*, a loosening) to this process of splitting up or decomposing a liquid: the liquid 'electrolysed' he called an *electrolyte* (λύειν, to loose): the metallic plate or end of wire which leads the current into the electrolyte he called the *anode* (*i.e. path up* the current): that which leads it from the electrolyte he called the *cathode* (*i.e. path down* the current), and each of them he also called an *electrode* (*i.e.* path for the electricity): the apparatus in which electrolysis occurs is called an electrolytic cell.

Decomposition of Water.—Small strips of platinum foil, to serve as electrodes, are attached to the ends of two platinum

wires: the wires are passed through fine glass tubes G whose lower ends are turned up and sealed so that the current can only escape to or from the electrodes by way of the plates or the short length of wire which is left exposed close to the plates.

Two wider tubes H, O, say 1·5 cm. (or ½ inch) diameter and 20 cm. (8 inch) long, are filled with water and, the ends being temporarily closed by the thumb, are inverted and placed in

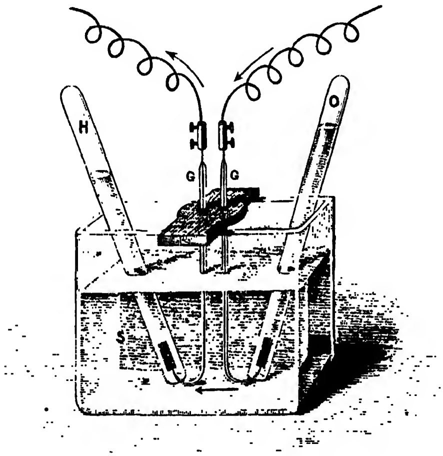


Fig. 66.—Decomposition of water by current.

the water in the trough S; they are then placed one over each electrode.

When the wires are connected with the poles of a battery of three or four cells, the water is rapidly decomposed: oxygen appears at the anode and bubbles up into the tube above it, while hydrogen travelling with the current bubbles into the tube at the cathode. The volume of hydrogen collected is found to be double that of the oxygen, thus verifying the well-known chemical formula for water H_2O.

Pure water conducts badly; a few drops of sulphuric acid should be put into it to improve the conduction. Platinum has a great power of occluding (literally hiding, *i.e.* absorbing) gases,

especially hydrogen: hence it is well to let the bubbling continue some time before collecting the gases in H, O, so that the occlusion may be complete before any measurement is made. To identify the oxygen, put a match with the end still glowing into the tube; the match bursts into flame. To identify the hydrogen set fire to it at the mouth of the tube.

Decomposition of Copper Sulphate.—If crystals of copper sulphate be dissolved in the water of the electrolytic cell the sulphate is decomposed when the current passes; copper is deposited on the platinum cathode, and oxygen bubbles are liberated at the anode; at the same time the liquid near the *anode* loses its blue colour, owing to the accumulation of the free sulphuric acid which has been robbed of its copper.

If, instead of platinum, we use a plate of copper for the anode, no free acid is formed, but the copper is eaten away, the same weight being dissolved at the anode as is deposited at the cathode.

The decomposition of sulphate or other salts of copper is utilised for many practical purposes. The earliest of these applications was made about 1839 in the invention of *electrotyping*, a method of taking exact copies of coins, engraved blocks, engravings of pictures, etc.

To copy a coin, a mould of paraffin wax, gutta-percha, or some special mixture is first prepared. A wax mould may be taken as follows: having slightly oiled the coin, wrap a piece of stiff paper about an inch deep round the rim and fasten with sealing-wax; warm the coin thoroughly and pour melted wax (not too hot) into this paper cup; when the wax has solidified it should be left for some hours in a cold place to become quite hard, before the coin is removed.

The impression is now carefully coated with fine black lead worked into it with a camel-hair brush, to render the surface conducting. Wax is a non-conductor, but black lead (which, we may remind the student, is merely graphite or pure carbon, and contains no lead whatever) conducts fairly well. An insulated copper wire is twisted round the mould to hold it, one bare end

being bent to press lightly on the front of the impression, and the other forming a hook for hanging the mould in the liquid. Wires from the poles of a single Daniell cell are connected to two copper bars, which are laid across a bath containing a solution of copper sulphate; a copper plate is hung from the + bar and the mould from the − bar; the mould with its black-lead coat, being the cathode, receives a deposit of copper, while the copper anode is eaten away; after a few hours the deposited

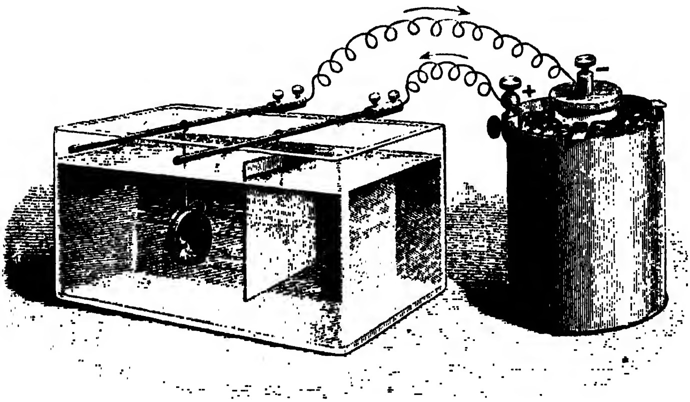


Fig. 67.—Electrotyping.

copper is thick enough to be removed, and a perfect reproduction of one face of the coin has been obtained.

Electric deposition is now employed on a large scale for the refinement of copper which has been extracted from its ores in a crude impure condition. The current required is obtained from dynamos (described later) instead of from batteries, but the principle of deposition is the same. A large slab of the impure metal is used as anode. The pure copper is deposited at the cathode, nearly all the impurities being separated at the anode fall to the bottom as a dirty powder; for example, any lead is converted into sulphate of lead which is insoluble; a little hydrochloric acid (HCl) is put into the liquid, so that any silver eaten

away from the anode is converted into silver chloride (AgCl), which is insoluble.

This process is specially well adapted for the manufacture of copper tubes, as the copper can be deposited on cylindrical cores, which are subsequently withdrawn and leave a weldless tube; if the copper be burnished continuously during deposition its tenacity is greatly increased.

Electroplating.—Before the great development of electric deposition in the year 1840, metals could be silvered or gilded only by cumbersome and expensive processes, which involved the use of amalgams of silver or gold (*i.e.* mercury with silver or gold dissolved in it), and were dangerous to workmen. About 1840 Messrs. Elkington and others succeeded in covering base metals electrically with coats of silver or gold, that is, they invented *electroplating*. The two chief difficulties to be overcome were, firstly, to find a salt of silver which would give a smooth regular non-crystalline deposit; and next, to secure a deposit which would adhere well to the base metal, and stand polishing without blistering or peeling off.

Silver Cyanide (AgCN) has been found to be the most suitable salt of silver. It is insoluble in water, but the addition of cyanide of potassium (KCN) to the water makes it dissolve readily. Many and various recipes are used by different electroplaters. The following is a good proportion for amateur work: '1 part AgCN, 4 parts KCN, 100 parts water.'

Perfect adhesion of the deposit can only be secured by the article which is to receive it being thoroughly clean. The cleaning of copper, brass, etc., is effected as follows: (1) place for a few minutes in a strong boiling solution of caustic potash, this is to remove grease; (2) swill well in clean water; (3) dip into dilute sulphuric acid; (4) rinse again; (5) dip for a second or two into strong nitric acid; (6) immediately rinse well in clean water till all trace of acid is removed: after the cleaning, care must be taken not to handle the articles, for the slightest greasiness thus acquired will cause the deposit to peel.

The method of depositing is the same as for copper; the

articles to be plated are suspended in a bath or vat of silver solution, they are connected to the negative pole of a battery, thus forming the cathode for the current. A plate of silver is connected to the positive pole and forms the anode.

Special precautions have to be taken to make the silver 'take' on places which have been soldered. Iron and steel can only be satisfactorily plated if first coated with copper, for which cyanide of copper dissolved in water containing cyanide of potassium may be used.

For *electrogilding* a solution of cyanide of gold in cyanide of potassium and water is used.

In all cases of plating the deposit must be formed slowly, otherwise it becomes irregular and of bad colour; an excessive current will deposit the metal as a dark loose powder; a good coat of silver takes from twelve to forty-eight hours to be deposited.

Laws of Electrolysis.—If several similar electrolytic cells, say of copper sulphate, be placed in series so that the same current passes through each in turn, we find, by weighing the cathode before and after, that the same weight of copper is deposited in each; or if water cells be used the same volume of hydrogen is set free in each. These results we might have expected, but an important and unexpected result is obtained when the current is passed through a series of cells containing different liquids—say (1) acidulated water, (2) nitrate of silver, (3) cyanide of silver, (4) copper sulphate, (5) copper acetate, (6) zinc sulphate—namely, the same weight of silver is deposited in each silver cell—whether from nitrate or cyanide—and the same weight of copper in each copper cell, whether from sulphate or acetate; and on comparing the weights of the different metals we find that for each gramme of hydrogen set free there are deposited 108 grammes silver, 31·5 ($\frac{1}{2}$ of 63) grammes copper, 32·5 ($\frac{1}{2}$ of 65) grammes zinc.

The chemical student will at once see the connection of these numbers with 'atomic weights,' but to the non-chemist we must explain that to every element (*i.e.* simple, non-compound sub-

stance) a number can be assigned which is proportional to the weight of an atom of the element; and since every molecule of a compound substance is built up of atoms of its constituents, it follows that the weights of the elements contained in any compound must be proportional to these numbers (or to some simple multiple of them); for example, a molecule of water H_2O being built up of two atoms of hydrogen (atomic weight 1) and one atom of oxygen (atomic weight 16), the weights of hydrogen and of oxygen are in proportion 2×1 to 16: a molecule of copper sulphate $CuSO_4$ being built up of 1 atom copper (atomic weight 63), 1 atom sulphur (32), and 4 atoms oxygen, the weights of copper, sulphur, and oxygen in the sulphate are proportional to 63, 32, and 4×16.

Again, the difference between nitric acid HNO_3 and silver nitrate $AgNO_3$ is that an atom of hydrogen has been turned out of each molecule of acid and replaced by an atom of silver, hence an atom of hydrogen and an atom of silver are chemically *equivalent to* (worth as much as) each other.

Similarly, comparing sulphuric acid H_2SO_4 and copper sulphate $CuSO_4$, we see that *two atoms* of hydrogen are equivalent to *one* atom of copper.

Hence 1 gramme of hydrogen is equivalent to 108 grammes silver and to $\frac{1}{2}$ of 63 grammes copper.

Our experiment, therefore, proves that *the weights of the different elements set free by the same current are proportional to their chemical equivalents.*

And remembering that the chemical equivalents are proportional to the weights of the atoms, it follows that *when a current passes through several cells in succession it causes the same number of atoms to be deposited in each cell;* except that in the case of *copper, zinc, lead,* etc. (dyads), we have *one half the number of atoms;* with gold, aluminium (triads) one-third the number, and often with tin one-quarter the number.

This remarkable result has suggested the idea that it is not merely by coincidence that electricity and matter travel together through the liquid, but that electricity is actually *carried* by the

matter, each atom taking with it its own charge and giving it up to the cathode (or anode); in other words, electricity travels through electrolytes by convection (as heat travels through liquids by convection). The evidence in favour of this view is rapidly accumulating.

Metals and hydrogen, which carry + electricity, are called *Electropositive* (Faraday called them Kations — *Wanderers down* stream).

Oxygen, chlorine, iodine, etc., which carry − electricity, are called *Electronegative* (or Anions—*Wanderers up* stream).

The weights of oxygen, etc., set free at the anodes are also proportional to their chemical equivalents.

TABLE OF ELECTROCHEMICAL EQUIVALENTS

Element.	Atomic Weight.	Valency.	Chemical Equivalent.	Electrochemical Equivalents.	
				Grammes deposited per sec. by 1 ampère.	Grains deposited per hr. by 1 ampère.
Electropositive					
Hydrogen	1	1	1	·00001038[1]	·576
Potassium	39·03	1	39·03	·000405	22·5
Gold	196·2	3	65·4	·000679	37·7
Silver	107·7	1	107·7	·001118	62·0
Copper (cupric)	63·18	2	31·59	·000328	18·2
,, (cuprous)	63·18	1	63·18	·000656	36·4
Tin (stannic)	117·4	4	29·3	·000305	16·9
,, (stannous)	117·4	2	58·7	·000609	33·9
Iron (ferrous)	55·88	2	27·94	·000290	16·1
Nickel	58·6	2	29·3	·000304	16·8
Zinc	54·88	2	32·44	·000337	18·6
Lead	206·4	2	103·2	·001071	59·5
Aluminium	27·04	3	9·01	·000093	5·19

[1] ·116 cubic centimetres.

CHAPTER IV

SECONDARY BATTERIES

Polarised cell—Charging—Discharging—Formation of Cell: Planté's Method —Faure's method—E.P.S. Cell—Function of Secondary Batteries.

Polarised Cell. — We saw on p. 725 how a copper plate which had become coated with hydrogen, or had as we described it, become 'polarised' by the passage of a current through a cell, could be used in company with a clean copper plate to produce a current in the opposite direction to the original current. Facts similar to this were utilised by Planté and Faure, and led to the construction of secondary batteries, in which lead plates were deliberately 'polarised' in order that they might subsequently yield a reversed or secondary current.

Charging.—To understand the action of a secondary battery let us first consider the behaviour of a cell in which two lead plates, A, B (Fig. 68) dip into dilute sulphuric acid. If a battery (or dynamo) be connected up to the terminals P and N on the plates so that a current passes from the anode A through the liquid to the kathode B, hydrogen is set free on B, the greater part escaping in the form of bubbles, and oxygen is set free on A. The oxygen, however, instead of escaping in bubbles is able to attack and eat into the lead plate, covering it with a reddish brown coat of peroxide of lead PbO_2, for oxygen in its nascent (new born) condition is far more active than at other times; after a time the peroxide coating becomes so thick as to prevent the

lead beneath it from being further attacked, the oxygen then escapes in bubbles.

Discharging.—If now the battery be disconnected and the terminals P and N connected directly by a wire, a current flows through the cell in the opposite direction to what it did previously; the terminal P thus becomes the positive and N the negative terminal of the cell. As this current flows, hydrogen makes its way to the plate A, and, combining with the oxygen of its peroxide coating, it gradually deoxidises it, reducing some of it to metallic lead in a porous spongy condition: on the other hand oxygen makes its way to the plate B and covers it with peroxide; as this process goes on, the strength of the current falls off, and finally it dies away when both plates are coated equally with peroxide. The cell is now 'discharged.'

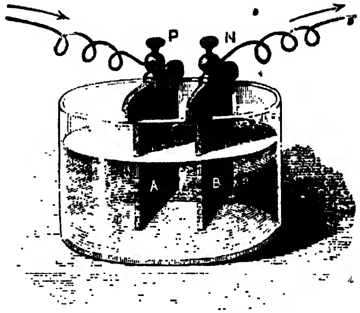


Fig. 68.—Primitive secondary battery.

Formation of Cell—Planté's Method.—If the battery be again connected to P and N, but in the opposite direction to the first connection, the current passes in the same way as during the 'discharging' process, hence the oxidisation of the plate B is carried further, and the deoxidisation of the plate A continues until its peroxide coat is entirely reduced to spongy lead. The cell may now be 'discharged' as before by connecting a wire from P to N, but in this case N acts as positive terminal.

The process of 'charging' and 'discharging' being repeated many times it is found that the time before oxygen bubbles appear on the positive plate during charging gradually increases; hence the coatings of peroxide on one plate and of spongy lead on the other increase, with the result that the discharge current also lasts longer.

The chemical actions in the cells are not, in fact, so simple as

described above, for a considerable amount of lead sulphate ($PbSO_4$) and of lead monoxide (PbO) are also formed, and this introduces complications into which we cannot enter here.

This method of 'formation' of the cell was devised by Planté, who was the first to construct a secondary cell of practical utility. It is, however, a tedious process.

Faure's Method.—In 1881 Faure introduced the improvement of coating the lead plates at the outset with a paste made up of red lead (Pb_2O_3) and dilute sulphuric acid; the charging process and the direct chemical action of the sulphuric acid

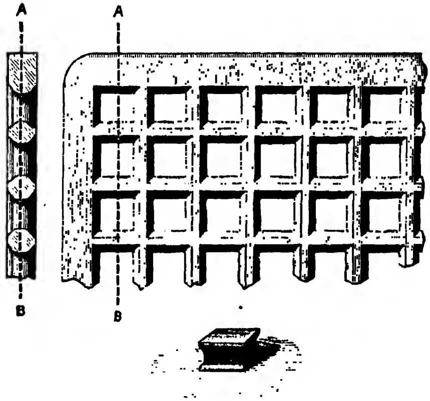


Fig. 69.—Lead grill and cake of compressed oxide.

on the red lead quickly produce the same condition of the plates as was obtained by the Planté process.

A very serious drawback to the Planté and Faure cells is that the coatings of the plates peel off after the cells have been in use for a short time. Recent improvements have been made to lengthen the life of the cell.

E.P.S. Cell.—A good type of a secondary battery now in use is the E.P.S. (Electric Power Storage) cell; in it the lead plates are replaced by leaden grills or gratings, as in Fig. 69. Each hole in the grill is filled with a cake of compressed oxide of lead, the holes being shaped so as to prevent the

cakes from falling out. A complete cell is shown in Fig. 70; instead of a single pair of plates it has five grills united at the top by the lead bar to which the positive terminal is attached, and six grills also united by a lead bar to which the negative terminal is attached; the effect is the same as that of a pair of plates of five or six times the size of a single one, hence the

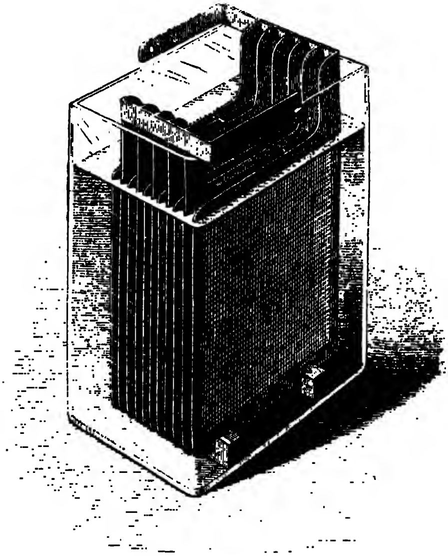


Fig. 70.—E.P.S. cell.

cell has a very low internal resistance (about ·001 to ·002 of an ohm). The liquid in the cell is dilute sulphuric acid.

Function of Secondary Batteries.—Originally, secondary batteries were called accumulators or storage batteries, because it seemed as if electricity was accumulated or stored up in them; the account we have given of them shows, however, that their real function is to transform electrical energy into chemical energy during the so-called 'charging'; and subsequently at any desired time to reconvert this chemical into electrical energy.

Secondary batteries are very useful for electric lighting

where an engine and dynamo are available for charging during the day, but where it is not desired to keep the engine running during the night; or again, for electric launches or carriages where the batteries may be charged at fixed stations and the current from the batteries can be used to drive a motor during the journey from one station to another.

They possess, however, two drawbacks: they are heavy, and they are not economical. The lack of economy arises in two ways: first, a higher E.M.F. is needed during charging than the cell gives while discharging [about 2·1 to 2·5 volts during charge and 2 to 1·85 volts during discharge], and secondly, if the current during 'discharge' be the same as during 'charge' it will last for a shorter time than the charging process occupied. On an average, about 30 per cent of the work done during the charge is wasted, the remaining 70 per cent being available for doing work during the discharge.

CHAPTER V

ELECTROMAGNETISM

Lines of Force due to Current—Current round a Loop—Solenoid—De la Rive's Floating Battery—Electromagnet—Electric Bells—Bell Push—Action of one Current on Another—Ampère's Stand—Roguet's Vibrating Spiral—Maxwell and Faraday's Treatment of Electromagnetism.

Lines of Force due to Current.—Consider a straight wire AB carrying a current, and a circle PQR surrounding the wire; a direct application of Ampère's or Fleming's rule shows that a

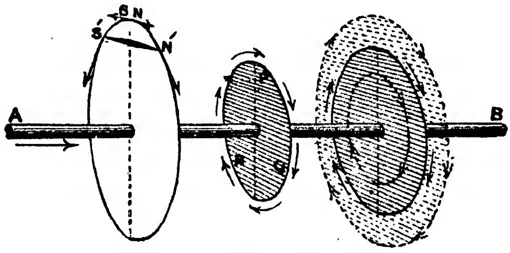


Fig. 71.—Lines of force due to current.

N. pole of a magnet placed at any point on the circle is acted on by a force tending to drive it round the circle in the direction of the arrows. Remember that we cannot get a magnet with a N. pole only, and that as the S. pole is urged in the reverse direction, we can never hope to see a N. pole careering along the circle round and round the wire; the utmost that can happen to an actual magnet is to twist round till it is at right angles to the wire, as SN in Fig. 71, then the pull on the N. pole is

directly opposed to the pull on the S.; if the magnet be longer in proportion to its distance from the wire (as S′N′) the two pulls will be inclined to each other (instead of directly opposite), and therefore they will have a resultant tending to pull the magnet as a whole nearer to the wire.

Hence *a wire carrying an electric current is surrounded by circular lines of (magnetic) force, and the direction of the current and of the lines of force are connected in the same way as the turning and driving in of a common right-handed screw* (Fig. 72).

The lines of force can be shown by passing a powerful current, say ten ampères, along a stout wire which has been stuck at right angles through a sheet of paper—or better, through a hole drilled in a sheet of glass—iron filings sprinkled on the sheet

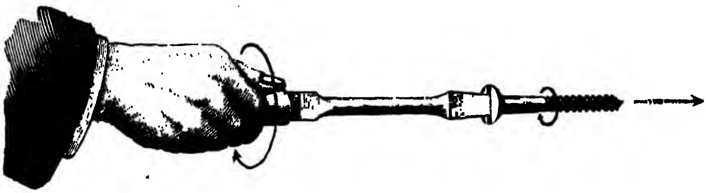


Fig. 72.—{ Current in direction 'Hand to Screw.' Lines of force in direction of twist.

arrange themselves, when the sheet is tapped, in circles with the wire for centre.

The resultant attraction on a complete magnet may be shown by the pretty experiment represented in Fig. 73. SN is a magnetised sewing needle floating on water; an insulated wire is bent over the edge of the bowl and then brought up vertically at the centre; when a current of three or four ampères is passed through the wire, the needle is drawn towards it; if the direction of the current in the wire be then reversed, the needle is first repelled, then it twists round with a graceful movement and finally is again attracted to the wire. It should be noticed that the middle of the needle comes up to the wire, not the point or the eye; hence it is the resultant of the forces on the *two* poles which causes the movement, not a direct attraction on either pole.

Current round a Loop.—If the wire along which the current passes be bent into a loop, the lines of force which encircle it will appear as in Fig. 74. For the sake of clearness in the figure we have imagined the loop closed by a disc of cardboard. The lines of force show that a N. pole placed anywhere just in

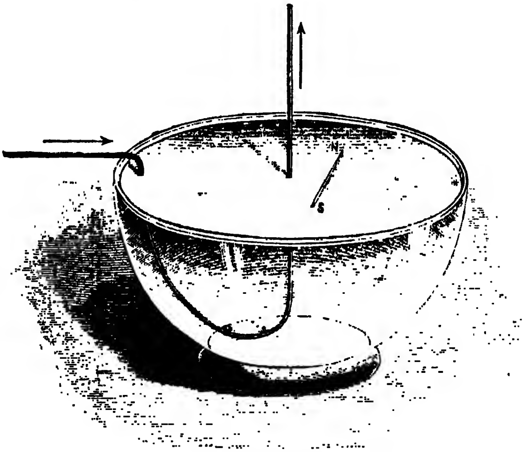


Fig. 73.—Needle attracted by current.

front of the card is driven forward towards us—*i.e. away* from the card, while a N. pole placed just behind the card is also urged forward towards us—*i.e. towards* the card. Now if we had a *steel* disc of the same size as the loop, and if it were magnetised so that the whole front surface was a N. pole, and the whole back surface a S. pole, this magnetised disc would act on a N. pole in exactly the same way as does the current in our loop.

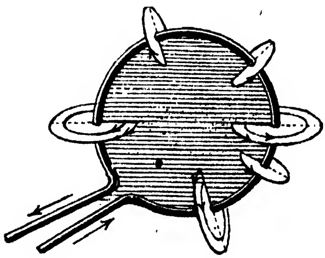


Fig. 74.—Lines of force due to a loop.

Notice that in the figure the current is flowing round the loop anti-clockwise; hence *an electric current flowing round a wire loop is equivalent to a flat magnetised disc (lamina) of the same size as the*

loop, the N. pole of the disc being on that face round which the current appears to flow anti-clockwise.

Solenoid.—Now bend the wire conveying the current into a spiral shape; each turn of the spiral is practically such a loop as

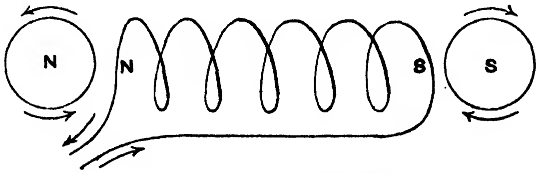


Fig. 75.—Current in spiral wire.

that just described, and is therefore equivalent to a magnetised disc; and the whole spiral is equivalent to a set of such discs all with their N. poles facing to the left (Fig. 76) and S. poles facing to the right; the alternate N. and S. poles neutralise each other (so far as external action is concerned), and there remains an unneutralised N. pole at one end and an unneutralised S. pole at the other.

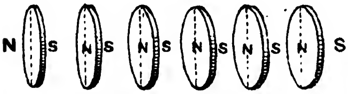


Fig. 76.—Equivalent magnetised discs.

A spiral wire carrying a current of electricity is called a Solenoid; *it is equivalent to a magnetised rod so far as concerns its action on bodies outside the spiral.*

Notice that we decide which end of the spiral will be N. and which S., *not* from the way of winding the spiral, *but by observing which way the current flows round.* If the current be reversed the poles are reversed, although the spiral itself is unchanged.

The circles N. and S. in Fig. 75 show how, looking at one end of the spiral, the current seems to flow 'clockwise,' and looking at the other end it appears to flow 'anti-clockwise.' There is, however, one important difference between a solenoid and a magnetised rod, viz., a N. pole can pass through and is attracted through the *interior* of a solenoid, *i.e.* the magnetic lines of force pass through the solenoid; but a magnetised rod being solid does not permit anything to pass through its interior.

Fig. 77 shows a section of solenoid with its lines of force. The magnetic forces due simply to an electric current are

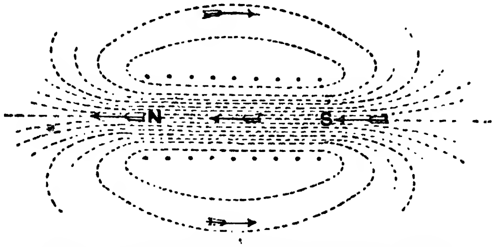


Fig. 77.—Section of solenoid showing its lines of force.

comparatively feeble; hence to ensure successful experiments it is advisable to use a big current—10 to 20 ampères.

De la Rive's Floating Battery.—This arrangement was designed by De la Rive to show the action of a solenoid.

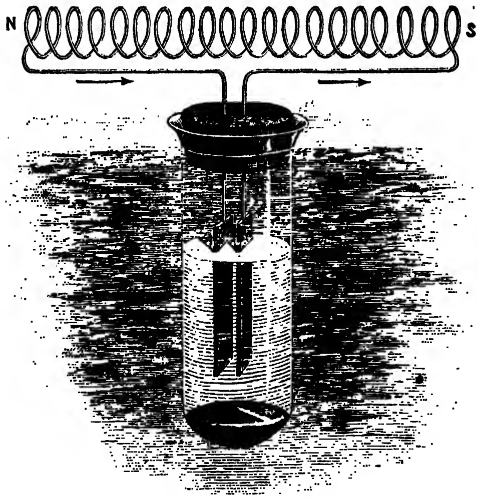


Fig. 78.—Floating battery.

A plate of copper and one of amalgamated zinc are fixed near to one another in a big test tube which is about half full of

dilute sulphuric acid; stout wires from the plates pass through a cork, and are continued above in a spiral of wire as shown in Fig. 78. The whole is floated in a trough of water, a little mercury being put into the tube to make it float upright. The current starting from the copper flows through the spiral wire back to the zinc. The spiral thus behaves like a bar-magnet with red

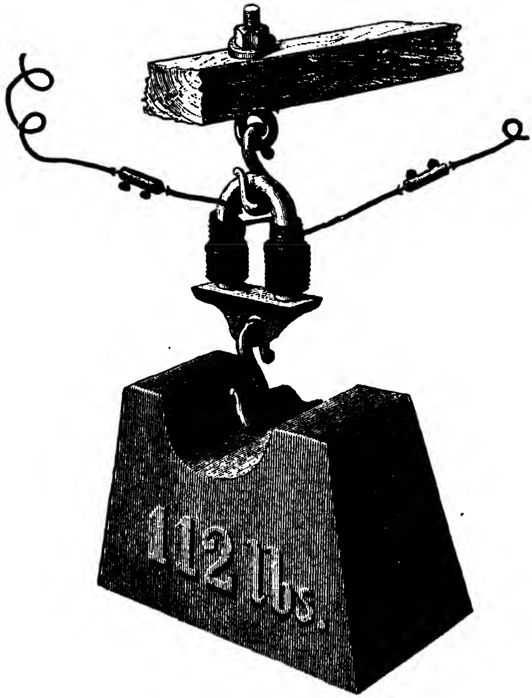


Fig. 79.—Small electromagnet.

pole at N, and will set itself pointing N. and S. just like a compass needle. Occasionally this turning is sluggish and undecided, but the attraction and repulsion caused by presenting the poles of a bar-magnet to S. or N. are always well marked.

Electromagnet.—If a rod of soft iron be placed within a solenoid, the rod becomes magnetised by magnetic induction

whenever the current passes; consequently the whole acts as a much more powerful magnet than the spiral without the iron (p. 629). De la Rive's floating battery will turn N. and S.

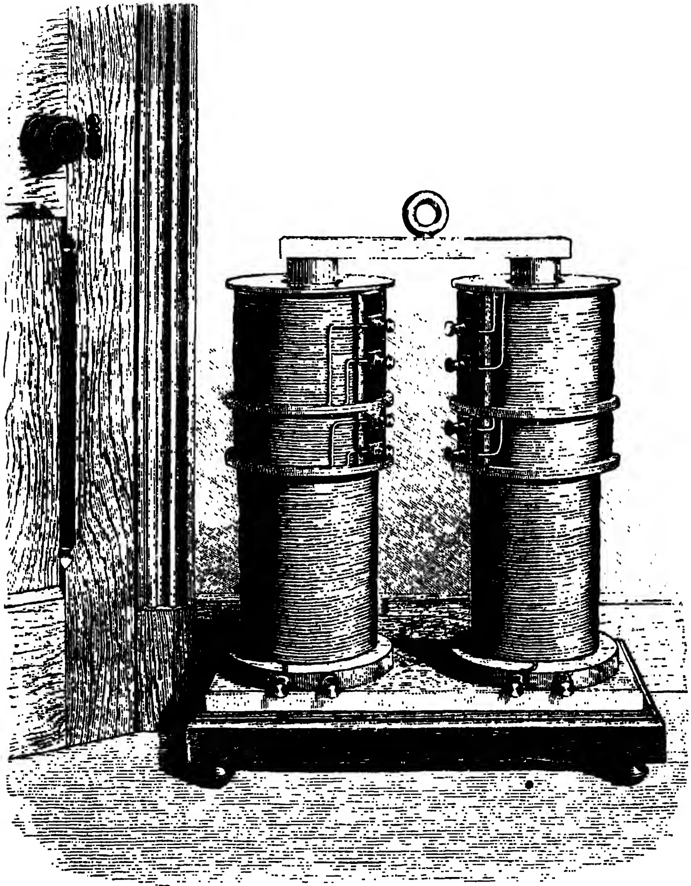


Fig. 80.—Large electromagnet.

without any hesitation when an iron rod is slipped into it. In doing this, however, care must be taken not to let the iron touch the wire of the spiral, for the current would then take

a short-cut through the iron from one turn of wire to the next instead of going round the spiral. Such a short-cut is called a **short circuit**, and has to be guarded against in all electrical experiments. So when a battery or dynamo has its terminals connected by a wire of small resistance, it is said to be **short circuited**.

We can prevent a short circuit in the solenoid either by folding the iron in paper or by using an insulated wire (covered with silk, cotton, or gutta-percha) to form the spiral.

When insulated wire is used, the spiral can be wound closely round an iron core, and, if several layers of wire be wound on to the core, the effect of a given current is much increased. The iron core wound round with insulated wire is called an ELECTRO-MAGNET. They may be shaped as bar-magnets or as horse-shoe magnets.

The magnet of Fig. 79 when supplied with current from a battery of three Grove cells will support about two hundred-weight hanging from the hook on the armature, while the powerful magnet of Fig. 80, if supplied with a current from a dynamo, could exert a force of many tons-weight.

Electric Bells.—We are now in a position to understand the action of an electric bell, a very simple and interesting application of an electromagnet to practical use.

An electromagnet M is fixed so that it can attract an iron armature A, and this is attached to a spring S, which carries a hammer H. The hammer strikes the gong whenever a current passes through the electromagnet. One end of the wire from the electromagnet is connected direct to the binding screw T; the other end is connected to the spring S, so that an electric current entering the bell at T will pass through the coils of M, and thence to the spring. At C a screw provided with a platinum point is adjusted so that the spring S presses lightly against it when at rest. The screw works in a brass block which is connected with the other binding screw T′, so that the current makes its way from the hammer spring to T′ by way of the 'contact' point.

It is easy to see that as soon as a current passes through the bell, the hammer spring is attracted away from the contact screw at C, thus the circuit is broken and the current ceases at the same time that a blow is struck on the gong. The current having ceased, the electromagnet no longer attracts the armature A; the spring therefore causes it to fly back against the contact screw. This again 'makes' the circuit; the current starts again,

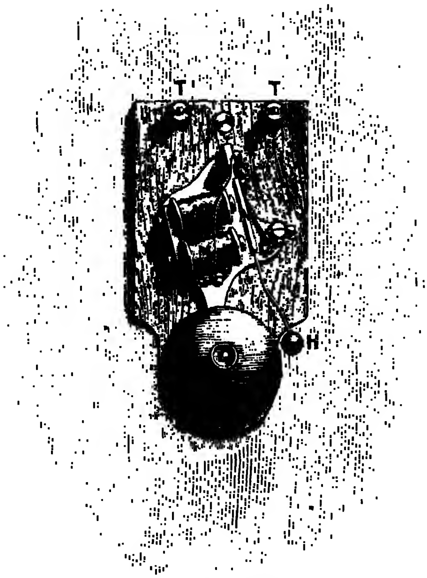


Fig. 81.—Electric bell.

and the hammer being again attracted strikes a second blow on the gong. The whole process is repeated, and a continuous ringing of the bell goes on so long as a wire from each pole of a battery is attached to each terminal of the bell.

In order that the bell may only ring when desired, the circuit is broken at any convenient place in either wire between the battery and the bell. In the gap thus formed is inserted a 'Push.'

Bell Push.—A simple form of push is shown in Fig. 82. A wooden or slate block A has a cover B which screws on to it, and a small 'button' C fits loosely in a hole in the cover. The ends of the 'broken' wire are brought through holes in the base block, and fastened by screws to the two metal strips D and E. One of these, E, is curved so that it is pressed into contact with the other, D, whenever the button is pushed.

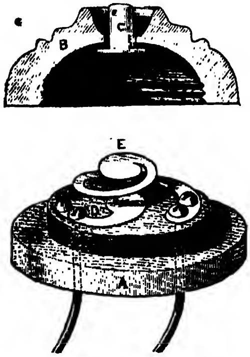


Fig. 82.—Bell push.

Fig. 83 shows how the same battery (two or three Leclanché cells) may be used to ring several bells. The current starting from the battery carbon has the choice of three routes—(1) through drawing-room; (2) through dining-room; (3) through door—by which to return to the battery zinc. Each route is interrupted by a push, and the current is

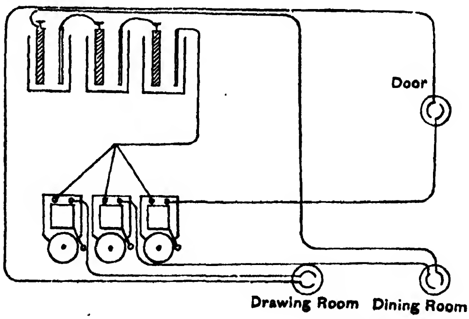


Fig. 83.—Several bells rung by one battery.

permitted to pass through any desired bell by pressing the corresponding push.

Action of one Current on Another.—Having seen that a current passing through a coiled wire (solenoid) is able to act on a magnet, attracting it as another magnet does, we might have expected that one solenoid would act on another, or even that a

straight wire carrying a current would act on another. Ampère discovered this as a fact in 1821, a year after Oerstedt's discovery of the action of the current upon a magnet.

Ampère's Stand.—The apparatus known as Ampère's Stand may be used to show these attractions and repulsions. In the form of it shown in Fig. 84, a hollow upright brass tube A is fixed on a base board, and is connected to a binding screw E. The other binding screw is connected by a wire passing through the base board to an insulated rod which passes up the inside of A, and carries a small steel cup B at its end. The hollow upright A terminates in the circular cup C. If now wires from a battery be made fast to the binding screws E, F, the circuit from the battery extends to C and B, but is there broken. Now let a well balanced wire rectangle PQRS be pivoted in the cup B, and have one end dipping in the cup C. In each cup a little mercury is placed to ensure a good 'contact.' The rectangle will (as seen, p. 750) face magnetic N. and S. when a strong enough current passes. Now bring near to PQ a wire UT parallel to it and carrying a current. If the current be in the same direction in both wires, PQ is attracted; if in the opposite direction, PQ is repelled. Hence *parallel currents [or the conductors along which they pass] if in the same direction attract, and if in the opposite direction, repel one another.*

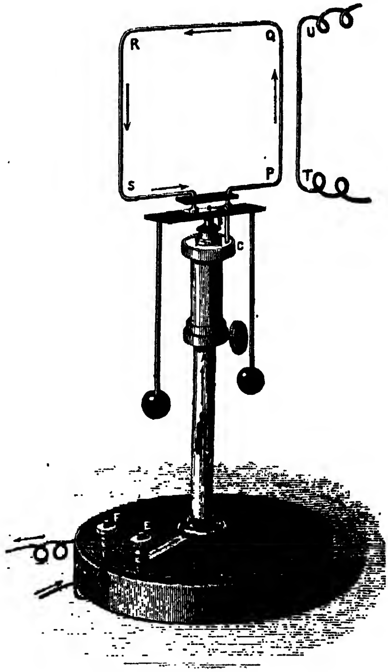


Fig. 84.—Ampère's stand.

Ampère's stand may also be used to show that a solenoid behaves like a magnet. The solenoid AB (Fig. 85) can be attached

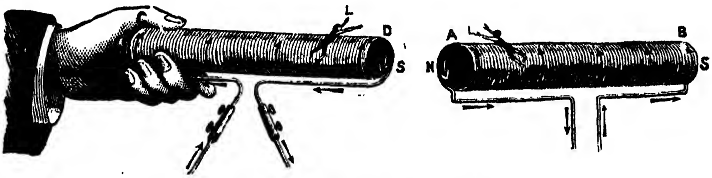


Fig. 85.—Solenoids on Ampère's stand.

to the balancing frame of the stand and have the ends of its wire dipping into the mercury cups. The solenoid CD held in the hand carries a current (which may either be the same current that has passed through AB, or be derived from a separate

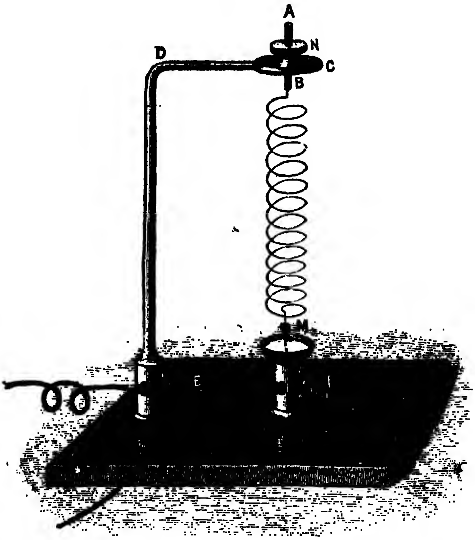


Fig. 86.—Roguet's vibrating spiral.

source). The S. pole of CD attracts the N. pole of AB when presented to it, whereas it repels the S. pole of AB.

Roguet's Vibrating Spiral.—The following pretty experiment shows the mutual attraction of currents flowing in the

same direction. A spiral is made of thin springy brass wire, having its consecutive turns rather close together. It is soldered at the top to the screw AB (Fig. 86), which passes loosely through a hole in the brass support CDE; the height of the spiral can be adjusted by means of the nut N. At its lower end the spiral carries a small weight which keeps it slightly stretched, and it ends in a platinum point which just dips into the mercury cup M. When wires from a battery are connected to the binding screws E and F, the current passing round the spiral causes each of the parallel turns to attract the next. The spiral is thus shortened, the point is lifted out of the mercury, and the circuit broken. This immediately causes the contraction to cease; the

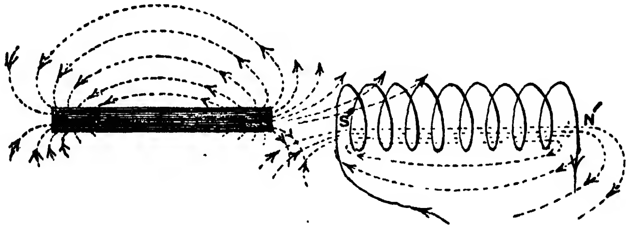


Fig. 87.—Lines of force of magnet and solenoid.

point descends and again touches the mercury, thus restarting the current. Hence the spiral is set into a regular vibration which can be detected by the buzzing sound (occasionally a musical note) produced, or by the sparking at the surface of the mercury.

Electromagnetism—Another Treatment.—The action of one current on another may be looked at from an entirely different point of view, one due to **Faraday** and **Maxwell**, namely, instead of considering the behaviour of a particular portion of the circuit, considering the lines of force due to the whole circuit. We then find that 'a circuit carrying a current tries to move so that as many lines of force as possible [due either to a magnet or to another circuit] pass through it in the same direction as its own lines of force.' Thus in Fig. 87 the lines of force of the magnet

SN and the solenoid S′N′ are shown, and clearly if the solenoid be sucked on to the magnet, it will embrace more of the magnet's lines of force. This movement is the same as that deduced on p. 750 from Ampère's law.

Also in Fig. 88, where the movable circular wire is in a plane perpendicular to the fixed rectangular wire, none of the lines of

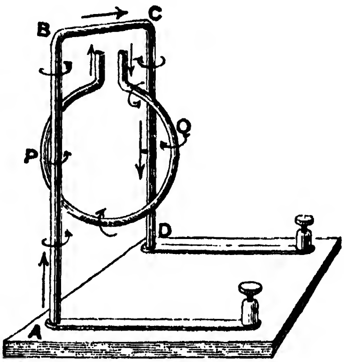


Fig. 88.—Movable and fixed circuits.

force of the fixed circuit pass through the movable one, but if the latter swing round so that P moves towards AB and Q towards CD, then a great number of lines of force will pass through it. Hence if it be free to move, the circular wire will swing in this direction until it is in the plane of the rectangle.

A Controlled Arc.—What has been said of a wire carrying a current applies to a current passing without a conductor. For example, the electric arc passing between two carbons (p. 804) behaves as the current-carrying wires described above.

CHAPTER VI

Electromagnetic Induction

Induction Experiments—Eddy Currents—Self Induction : Extra Current—Ruhmkorff Induction Coil—Use of Condenser.

Electromagnetic Induction.—We have so far seen how electric currents can make magnets, and behave like magnets, and the question naturally presents itself, 'Can magnets (or currents behaving like magnets) produce currents of electricity?' The researches of Faraday dating from 1831 answered the question in the affirmative, and from the facts discovered by him the knowledge which renders possible the construction of the gigantic dynamos of the present day has gradually been built up.

The following are the leading experiments proving the existence of electromagnetic induction.

Induction Experiments.—A (Fig. 89) is a coil of insulated wire wound on a hollow wooden reel. B is a similar but smaller coil which can be slipped into A. From the binding screws of B wires are carried to a galvanometer, and from those of A wires are carried to two small mercury cups, into which can also be dipped the ends of wires from a battery.

Experiment 1.—If, while one coil is standing within the other, the battery be connected with A, the galvanometer needle gives a sudden kick in the direction which indicates that a current has passed round B in the *opposite direction* to that in A : after its first kick the needle settles down to rest in its normal position (although the current continues in A), showing that the

current induced in B is only momentary, and is caused by the *starting* of the current in A.

Now break the circuit at one of the mercury cups, the galvanometer needle again gives a kick, but in the opposite direction to the previous one: hence the stoppage of the current in A causes an induced current in B in the *same direction* as the current in A; this induced current also is only momentary.

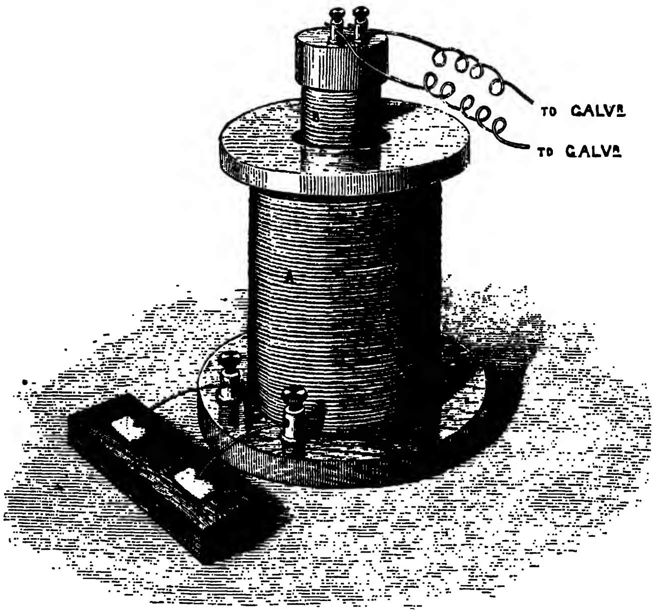


Fig. 89.—Electromagnetic induction.

It is convenient to call the circuit which is connected to the battery the *primary* circuit and its current the *primary* current: while the induced current and its circuit are called *secondary*. If the secondary current flow in the same direction as the primary it is called *direct*, if in the opposite direction it is called *inverse*.

Hence—

Starting a Primary current induces *Inverse* Secondary current.

Stopping a Primary current induces *Direct* Secondary current.

Experiment 2.—Connect the primary coil A (B having been previously taken out) to the battery; then rapidly *insert* the secondary coil into the primary, the galvanometer shows an *Inverse* current. When the needle has settled to rest, suddenly *remove* the secondary coil from A, the galvanometer shows a *Direct* current.

In the above experiments it is immaterial whether the outer or the inner coil be made the primary.

Hence—

'Placing the secondary coil within the primary,'

'Placing the primary coil within the secondary,'

or 'Starting the primary current when the coils are in place,' —all induce the same effect, viz. a *momentary Inverse current,* and the converse acts of 'taking out' or a 'stopping' induce a *momentary Direct current.*

Experiment 3.—The diagram in Fig. 90 shows B used as primary being pushed into A and the inverse current induced thereby in A.

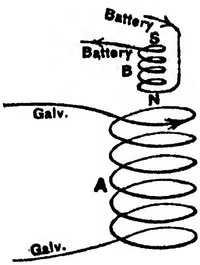


Fig. 90.—Primary coil being put into secondary.

Now B is merely a powerful solenoid with its N. pole downwards, and we have seen that solenoids are in many ways similar to bar-magnets, hence instead of the solenoid let us try the effect of inserting a bar-magnet into the secondary coil as in Fig. 91. We find that a current is induced in the same direction as that induced by the solenoid.

It is inappropriate here to speak of the induced current as 'Inverse,' since there is no primary current with which to compare it; we will therefore consider **Lenz's law**, announced in 1834, which applies to all cases.

"Whenever a current is produced by induction, whether by movement of magnets or wires, *the direction of the induced current is such as to resist the movement* which produces it."

For example, in Figs. 90 and 91 the induced current

gives a N. pole at the top, and this by its repulsion opposes the approach of the N. pole of the descending magnet or solenoid.

The law is one that it would *a priori* be reasonable to expect

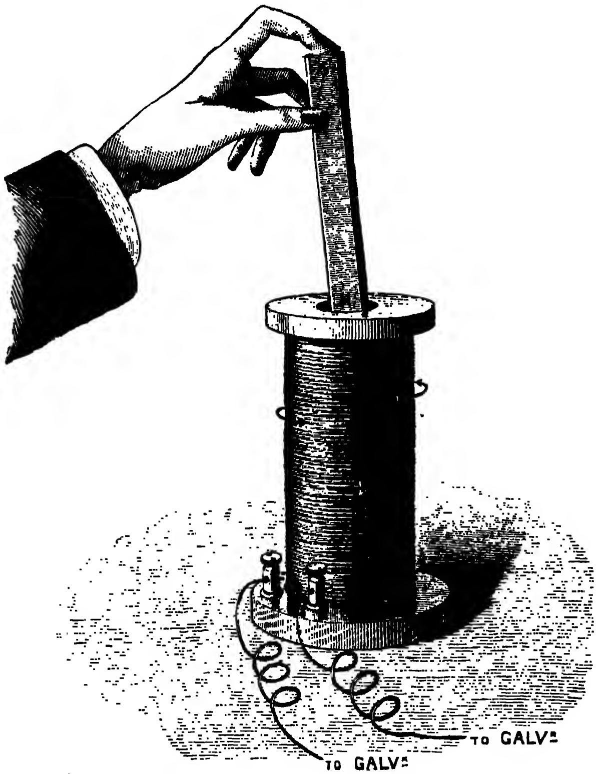


Fig. 91. –Current induced by magnet.

to hold good, for we *ought* to have to *do work* in order to produce a current in the secondary coil.

The induced currents in Experiments 1 and 2 are feeble and difficult to detect unless a very delicate galvanometer be used, but by placing a soft iron core or a bundle of iron wires within B a very powerful effect is produced both when B is used as a

primary (it is then, of course, an electromagnet) and when B is used as a secondary.

Experiment 4.—We may vary the third experiment as fol-

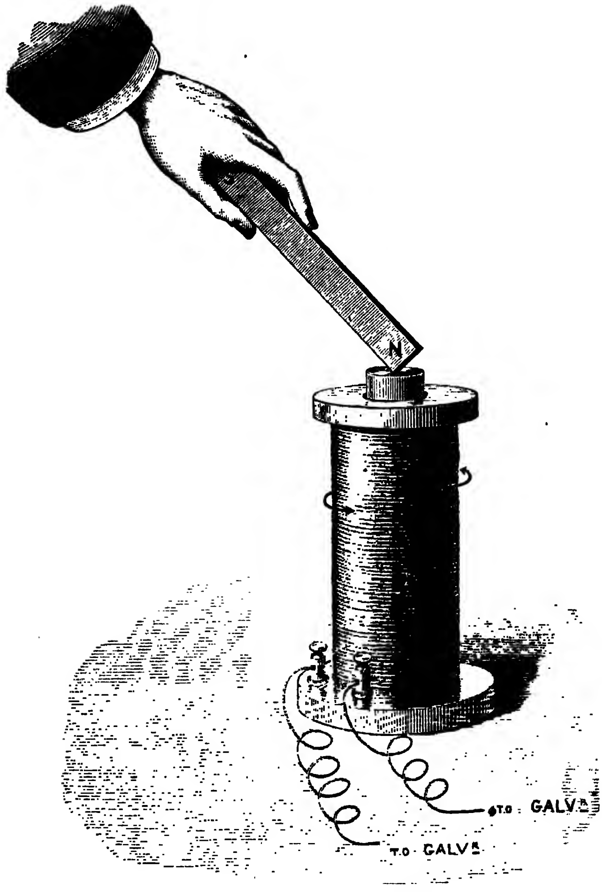


Fig. 92.—Induction by contact with soft iron core.

lows: Place a bar of soft iron within the secondary coil (or use one of the electromagnets (Figs. 79, 80) which are ready wound on soft iron cores); suddenly bring the N. pole of a bar-magnet

in contact with the core (Fig. 92): the latter becomes magnetised by (magnetic) induction. It will have a N. pole below and a S. above; hence the effect will be the same as if a bar-magnet had been rapidly inserted in the coil—there will be a momentary induced current as before. Now remove the bar-magnet, the core loses its magnetism immediately, and a current in the opposite direction is induced in the wire.

It is easy to see that if, when the N. pole is touching the core, the bar-magnet be rapidly reversed and the S. pole made to touch the core, we shall get an induced current twice as great as before.

In all the above experiments some effect, though a smaller one, is produced when the magnet or the primary circuit is moved nearer to or further from the secondary coil, instead of

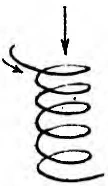


Fig. 93.—Lines increasing.

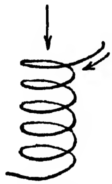


Fig. 94.—Lines decreasing.

placing it completely in or taking it completely out of the secondary.

The phenomena of induction may be summed up as follows (instead of as in Lenz's law): (1) Whenever the number of lines of magnetic force passing through a circuit is increased or decreased a momentary current is induced in the circuit.

(2) If the number of lines be *increasing*, the direction of the lines of force and of the induced current are connected by the left-handed screw movement (Fig. 93); if the number of lines be *decreasing*, the direction of the lines and of the induced current are connected by the common right-handed screw movement (Fig. 94).

If the secondary circuit be not complete no current can pass round it, but there will still be an electromotive force set up in

it; and it has been proved that whether the circuit be 'complete' or 'broken'—

$$\text{(3) The } \textit{induced E.M.F.} = \left\{ \begin{array}{l} \text{rate at which lines of force are re-} \\ \quad \text{moved from the circuit.} \end{array} \right.$$

Now by winding a large number of turns of wire on a coil we increase the number of lines of force passing through it, hence the induced E.M.F. is greatest when many turns are taken.

Eddy Currents.—If a block of metal be moved in the presence of a magnet, induction comes into play just as much as when a coil or a wire is so moved; an E.M.F. is set up in various parts of the block and causes currents of electricity to flow within it. These induced currents have no regular channel, such as a coil or a wire provides, in which they must flow, but they swirl about and form eddies. Induction thus acts on the electricity of the metal block in much the same way as, say, a wind blowing over a pond; there, the water being dragged forward in some places must necessarily flow back in others so that whirling eddies are set up; whereas in a canal the current may flow steadily forward just as a current along a wire. Attention was first directed to the existence of eddy currents by Foucault; they are often named after him **Foucault currents.**

Eddy currents may be detected by a very pretty application of Lenz's law in the following experiment. A sixpence or any light coin is attached to the end of a straw, which is suspended so that it can swing like a pendulum; the coin, which forms the 'bob' of the pendulum, passes at the lowest point between the poles of a powerful electromagnet, such as the one shown in Fig. 80. When no current is flowing in the electromagnet the pendulum will swing quite regularly. But when the current is flowing, the coin on being raised high on one side and let fall, swings rapidly to the lowest point, and there in endeavouring to cross the magnetic field it meets with the resistance which Lenz's law tells us is offered to any motion which tends to produce induced currents; the coin therefore is stopped almost dead, or at any rate it rises only a slight distance on the other side.

In dynamos and apparatus where massive pieces of metal are moved in a magnetic field, it is desirable that the metal should be provided with slots, or even built up of thin sheets, in order to check the formation of eddy currents; these currents have two disadvantages, they produce heat, and they add to the labour of driving the apparatus.

Self-Induction: Extra Current.—When a current passes round a coil, a number of its own lines of force pass through the

Fig. 95.—Sparking due to self-induction.

coil. If then the current be stopped, the sudden disappearance of these lines of force induces an E.M.F. in the direction in which the current was flowing, it therefore tends to prolong the current, and a spark often occurs at the point where the circuit is broken. This phenomenon is called *Self-Induction*, and the current produced by it is called an Extra Current. When using a coil with many turns of wire the E.M.F. due to Self-Induction at 'break' may far exceed the E.M.F. of the battery which produced the

original current. Conversely, Self-Induction opposes the starting of the current.

The effect of having a great number of lines of force through the circuit may be shown thus: hold a wire coming from one terminal of a single cell (say a Leclanché) in contact with a file, then draw the other wire along the file; as each ridge is crossed the current is started and stopped but no effect is visible. If, however, an electromagnet be interposed in the circuit the in-

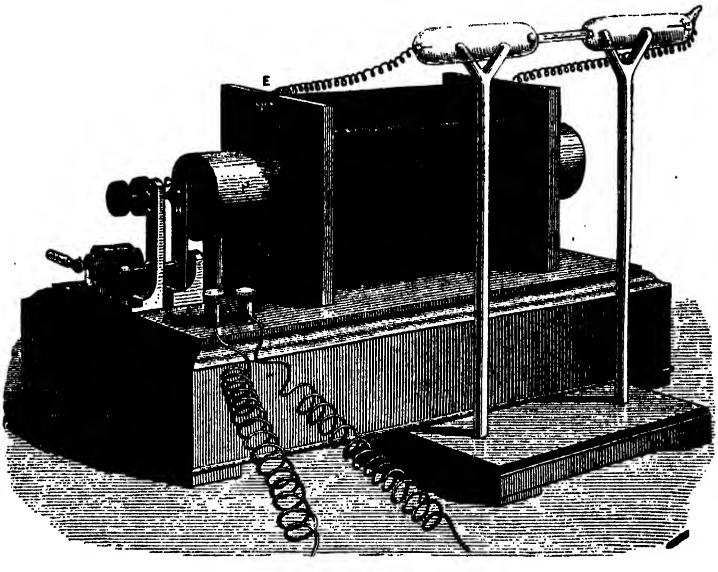


Fig. 96.—Ruhmkorff's coil.

crease of Self-Induction causes a series of bright sparks as the circuit is broken at each rib of the file (Fig. 95).

Ruhmkorff's Induction Coil.—Electromagnetic induction has been utilised to obtain a very high E.M.F. (from a thousand to many million volts), when there is at our disposal a battery of only moderate E.M.F. (one or two volts up to a hundred volts).

The Ruhmkorff coil consists in the first place of a primary coil P (Fig. 96) of fairly thick insulated wire wound round a soft

iron core (the core is often a bundle of iron wire), the ends of the wire of this coil are brought to the binding screws A, B, to which are connected the battery wires. A hammer H attached to a stiff spring vibrates as in an electric bell and alternately 'makes' and 'breaks' the circuit at the contact point C between the primary coil and the binding screw A. A secondary coil S surrounds the primary and consists of many thousand turns of a very fine wire whose ends are brought to the terminals E, F.

When the hammer vibrates, the E.M.F. induced in the secondary coil causes a rapid succession of sparks one or two centimetres in length between the ends of wires inserted in E and F.

In a gigantic Induction coil made for Mr. Spottiswoode the primary coil contained 602 metres (660 yards) of copper wire ·244 cm. (·096 inch) diameter, and its resistance was 2·3 ohms. The secondary coil contained 450 kilometres (280 miles) of wire $\frac{1}{1000}$ inch diameter; it had nearly half-a-million turns, and its resistance was 110,200 ohms. This coil gave a spark more than a yard (42 inches) long.

Use of Condenser.—The high Self-Induction of the primary coil of a 'Ruhmkorff' causes a high E.M.F. in it when the circuit is broken, which would, if not provided for, produce at the contact point C such intense sparking that the platinum points would be injured even if not completely fused and welded together (a frequent trouble in the early forms of coil). Besides this obvious disadvantage of the sparking, it is detrimental in another way; so long as the spark lasts, some current must be passing, hence with a long spark the primary current 'tails off' gradually instead of stopping sharply, and this means a great falling off in the E.M.F. induced in the secondary coil, for the E.M.F. depends on the *rate* at which the lines of force disappear from the circuit.

To prevent the excessive sparking a condenser (*i.e.* a modified Leyden jar, see p. 688) is fitted in the wooden base of the instrument. It consists of several sheets of tinfoil separated by sheets of paraffined paper: these are represented diagrammatically in

Fig. 97, a large condenser may have several hundred sheets, but only a few are given in the diagram. Alternate strips of foil are connected together at M and N so that they practically form two big sheets: M and N are connected with the metal blocks which support the hammer and the contact screw. Thus the 'extra current' instead of sparking slowly across the gap at C rushes suddenly as a positive charge into the condenser at N:

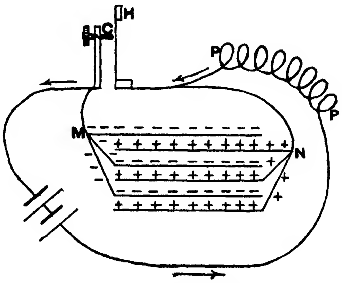


Fig. 97.—Diagram of condenser.

the foils connected to M receive at the same time an equal negative charge [from the negative current which we must remember always flows in the opposite direction to the positive current, although we seldom allude to it]. The condenser therefore enables the primary current to stop quickly; but it does more than this, no sooner is the condenser charged than it discharges itself through the primary, sending a reverse current through it, and so further augmenting the E.M.F. induced in the secondary.

Transformers.—Induction coils—called Transformers—are now much used by electrical engineers in order to obtain a heightened or lowered E.M.F. As in the Ruhmkorff coil, two coils (or two sets of coils), one a primary and one a secondary, are wound upon the same iron core, and currents are induced in the secondary by means of rapid changes of current in the primary. But, while the Ruhmkorff coil is *supplied with a direct current* (*i.e.* a continuous current always flowing in the same direction) from a battery, this current being artificially inter-

rupted by the vibrating hammer, the Transformer is *supplied with an alternating current* from a dynamo (see p. 834).

Fig. 98, though not based on actual measurement, represents the character of the variations of current in the primary and of the E.M.F. in the secondary of a Ruhmkorff, with condenser disconnected, when the hammer vibrates 100 times a second.

The current in the primary of the Ruhmkorff being broken very abruptly gives rise for an instant to a *very* high E.M.F. in the secondary, but this E.M.F. is maintained for a very short time only,—so short, indeed, that only a small quantity of electricity is able to pass through the secondary before the

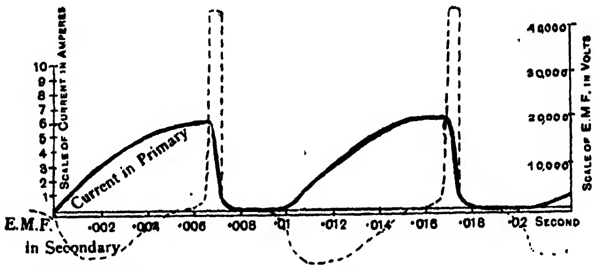


Fig. 98.—E.M.F. and current in Ruhmkorff coil (without condenser).

E.M.F. has ceased. The current in the primary then falls to zero, but is not reversed in direction (except for the back flow from the condenser spoken of above); then when the hammer 'makes' contact again, the current rises, rapidly, it is true, yet slowly compared with the abrupt 'break,' and causes in the secondary an E.M.F. opposite to that of the break, and so much lower than the latter that it is not, as a rule, able to overcome the resistance of the spark-gap, and is, therefore, not able to produce any current in the secondary.

The alternating current supplied by a dynamo to a Transformer first flows in one direction, gradually rising to a maximum, then gradually falling to zero; its direction is then reversed, and it rises to a maximum in the reversed direction; from that it falls to zero, and is again reversed, and so on. Hence the alternating current really consists of a series of electric waves or impulses

oscillating in the conducting wires: the rapidity of oscillation depends on the speed of the generating dynamo, and in practice ranges from, say, twenty to a hundred waves per second.

The character of the variations of a typical alternating current may be represented by a curve of sines (p. 427), though the shape of wave is modified by the design of the generating dynamo. In order to drive such a current through the primary coil of the Transformer a varying difference of Potential must be maintained between the terminals of the primary. This difference of Potential is usually spoken of as 'an impressed E.M.F.' applied to the terminals. It is composed of two parts: (*a*) the impressed E.M.F. needed to overcome the ohmic resistance of the primary—this part is comparatively small, owing to the low resistance of the coil; (*b*) the impressed E.M.F. needed to balance the back E.M.F. which is induced in the coil. Both of these parts pass through a series of alternations similar to those of the current, hence the variations of the impressed E.M.F. may also be represented by a sine curve.

Now the E.M.F. induced at any instant in the secondary coil is equal to the rate at which the total number of magnetic lines of force (also called the Total Induction or Flux) through the coil is increasing or decreasing—care being taken to count each line of force twice if the wire of the coil pass twice round it, fifty times if the wire pass fifty times round, and so on. Also the back E.M.F. induced in the primary is equal to the rate of change of induction through it; hence the changes in the E.M.F. produced in the secondary keep time with those of the back E.M.F. in the primary, and the E.M.F. would in fact be at every instant the same in both if the number of turns in primary and secondary were equal. Hence, remembering that the part (*a*) of the impressed E.M.F. is very small, we see that the E.M.F. impressed at the terminals consists mainly of the part (*b*), and is therefore practically equal to the back E.M.F. From this it follows that the Transformation Ratio

$$\frac{\text{E.M.F. of secondary coil}}{\text{E.M.F. of primary coil}} = \frac{\text{Number of turns in secondary}}{\text{Number of turns in primary}} \ (\textit{very}\ \text{nearly}).$$

Hence we have two classes of Transformers: first, Step-down Transformers, having fewer turns in the secondary than in the primary; these are used at a distance from the generating station to replace the current arriving through the mains at a high potential by a greater current at a corresponding lower potential required for use in lamps and motors. Secondly, there are Step-up Transformers, having fewer turns in the

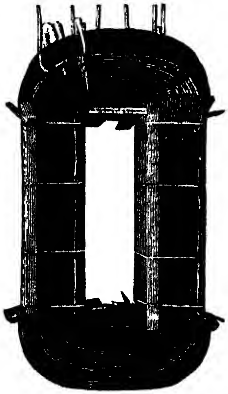


Fig. 99.—Coils of Transformer.

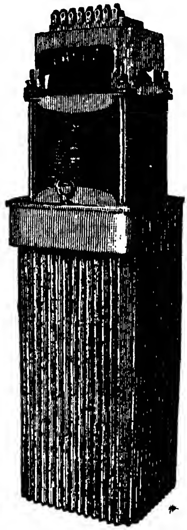


Fig. 100.—Transformer and case.

primary; these are used at the electric-supply station to convert a moderate E.M.F. produced by the dynamo into a high E.M.F. in the mains.

Modern alternators are, however, more frequently designed to furnish the desired high-tension current.[1]

The advantage gained by transforming lies in the fact that it is more economical (in cost of copper, etc.) to send a small current at high pressure through a small main than to send a big current at low pressure through a big main.

[1] Practical men speak of 'high-tension' currents, etc., when they mean high-pressure, high E.M.F. or high potential currents, etc.

Fig. 99 shows the coils of a 20 kilowatt Transformer, and Fig. 100 the complete Transformer lifted half-way out of its case.

The figures are from photographs of a 'Step-up' Transformer of the pattern used by the British Westinghouse Electric and Manufacturing Company. This Transformer has eight coils; four primary or low-pressure coils, wound on an oblong mould, and four secondary or high-pressure coils, wound on a mould so as to allow more space for insulation. These are brought together, a usual plan being to divide the low-pressure coils equally, and to place the high-pressure coils between them. Each set of coils is then connected up in series, and the wires from them brought up to the terminals on a marble block; they are insulated by sheets of rope-paper and fuller-board placed between the coils. The case is filled with oil of a high insulation resistance.

In Fig. 100 is seen the iron core which is put on after the coils have been assembled, and consists of sheet-iron stampings built up round the coils and bolted together to form a compact mass. This built-up sheet-iron core is preferable to a solid core, because it diminishes the formation of eddy currents in the iron, which heat the core and diminish the efficiency of the Transformer.

The iron is spoken of as a 'core,' although the coils are almost buried in it, instead of it being buried in the coil; for it has the same duty to perform in either case, namely to concentrate the magnetic field due to the current in the primary.

CHAPTER VII

Electrical Measurements

Unit Current—Unit Resistance—Unit E.M.F.—Unit Quantity—Unit Capacity—Unit Power—Galvanometers—Tangent Galvanometer—Reflecting Galvanometer—Ammeter—Voltmeter—Cardew's Voltmeter—Ohm's Law—Measurement of Resistance — Numerical Illustrations — Wheatstone Bridge—Post-Office Box.

All the units employed in the measurement of electricity are based on the use of the centimetre as unit of length, the gramme as unit of mass, and the second as unit of time; we therefore also take the dyne as the unit of force, and the erg as unit of work. The units thus determined are known as 'absolute' or 'C.G.S.' (centimetre-gramme-second); for practical purposes other units, which are simple fractions or multiples of these, are used.

Unit Current.—The standard current is one which, flowing along a wire of length one centimetre bent into a circular arc of radius one centimetre, exerts a force of one dyne on a Unit Magnetic Pole placed at the centre of the circle (Fig. 101). The practical unit of current is the Ampère, and is equal to a tenth of an absolute unit.

1 Ampère $= \frac{1}{10}$ C.G.S. unit of Current.

Unit Resistance.—The standard resistance is that of a wire which requires one erg of work each second in order to force the standard current through it. This unit is too small for ordinary purposes, the practical unit of resistance is the Ohm, and is equal to 10^9 (a thousand million) absolute units.

1 Ohm $= 10^9$ C.G.S. units of Resistance.

N.B.—It is impossible without weeks of refined experiment by the most skilled observers to ascertain the resistance of a wire measured in ohms in the manner described in the above abstract definition: a committee of experts decided in 1892 that the resistance of 14·4521 grammes of pure mercury at 0° C. formed (in a tube) into a column 106·3 centimetres long should be taken as the nearest attainable approach to the theoretical ohm; and 'Standard Ohms' have been prepared equal in resistance to such a mercury column. Other resistances must be compared directly or indirectly with these standards. The standards are coils of wire made from a suitable alloy of platinum.

Unit E.M.F.—The Standard Electromotive Force is that which is required to drive a Unit Current through a Unit Resistance. The practical unit of E.M.F. is the Volt, and is equal to 10^8 (a hundred million) absolute units.

$$1 \text{ Volt} = 10^8 \text{ C.G.S. units of E.M.F.}$$

Unit Quantity.—The Standard Quantity of Electricity is the amount conveyed in one second by a unit current. The practical unit of quantity of electricity is the Coulomb, and is equal to one-tenth of an absolute unit.

$$1 \text{ Coulomb} = \tfrac{1}{10} \text{ C.G.S. unit of Quantity.}$$

Unit Capacity.—The Standard Capacity is that of a condenser (Leyden jar) which requires a unit E.M.F. to charge it with a unit of electricity. The practical units of capacity are the Farad, which is $\frac{1}{10^9}$ of the absolute unit, and the Microfarad, which is one-millionth of a Farad.

$$1 \text{ Microfarad} = \frac{1}{10^{15}} \text{ C.G.S. unit of Capacity.}$$

Other practical units are the following:—

Unit Power.—A WATT is the rate of working when 1 ampère is driven through 1 ohm resistance.

746 Watts = 1 horse-power.

Unit of Work.—(*a*) A JOULE is the work done by 1 ampère flowing for one second through a resistance of 1 ohm.

$$1 \text{ Joule} = 10^7 \text{ ergs.}$$
$$1 \text{ Board of Trade Unit} = 3{,}600{,}000 \text{ joules.}$$
$$= 36 \times 10^{12} \text{ ergs.}$$

(*b*) A KELVIN or "BOARD OF TRADE UNIT" is the work done by 1000 watts (a Kilowatt) in one hour.

$$1 \text{ Board of Trade Unit} = 2{,}670{,}000 \text{ foot-lbs.}$$

Galvanometers.—On p. 723 we described a very rough form of galvanometer which merely indicated the passage of a current without being able to *measure* it accurately. We will now consider some improved forms. Let us first repeat that there are two units or standards for electric currents. (1) The Absolute Electromagnetic C.G.S. unit. This is one which, flowing along a wire 1 cm. long bent into an arc of a circle 1 cm. radius, exerts a force 1 dyne on a unit magnetic pole placed at the centre of the circle. Thus in Fig. 101, if 1 C.G.S. unit flow along the wire ABCD, the force thrusting the unit pole M to the left is 1 dyne.

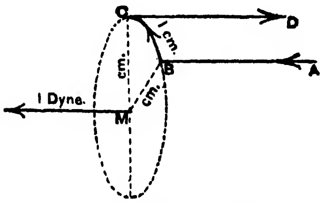


Fig. 101.—C.G.S. unit current.

(2) The Ampère, which is $\frac{1}{10}$ of the Absolute Unit, and is always used in practical work.

If a greater length of 'current-carrying wire' act on the magnet pole, the force is proportionately increased; if the distance of the wire from the pole be increased, the force is decreased in proportion to the square of the distance; also the force is proportional to the current.

Example.—Let a current of 70 ampères (7 C.G.S. units) flow round a coil whose radius is 10 cm., and which has 13 turns of wire. The circumference is $2\pi 10 = 63$ cm. (approximately); hence the force on a unit magnet pole placed at the centre is

$$\frac{7 \times 63 \times 13}{10^2} = 57 \cdot 3 \text{ dynes (approximately).}$$

Tangent Galvanometer.—This instrument in its simplest form consists of a single ring of stout copper wire mounted on a convenient stand which has three levelling screws. At the

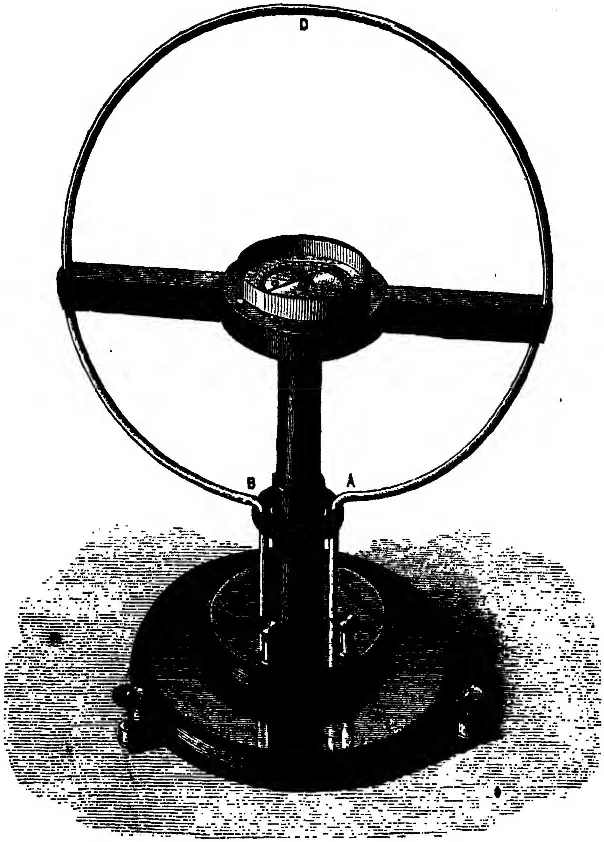


Fig. 102.—Tangent galvanometer.

centre of the ring is a short magnetised needle (length not exceeding say $\frac{1}{10}$ diameter of circle). The needle is supported by an agate cap on a sharp point, and usually has attached to it at right angles a long pointer of glass or aluminium whose

position can be read off by a graduated circle. The instrument is set with its ring in the plane of the magnetic meridian, and the pointer should then stand at zero.

In order to measure the current it is necessary to know (1) the earth's horizontal intensity H (see p. 653); (2) the radius 'r' of the ring; (3) the length 'l' of wire ADB, which acts on the needle. If then a current produce a deflection θ, the measure of the current can be found as follows: a current C exerts on a unit pole placed at the centre a force $\frac{Cl}{r^2}$ dynes. Now the poles N and S of the magnet are so near to the centre that the force on them does not appreciably differ from what it would be at the centre; hence if 'm' be the strength of each pole, the force on each is $\frac{Clm}{r^2}$ dynes; the force on the N. pole urges it eastward, and that on the S. pole urges it westward.

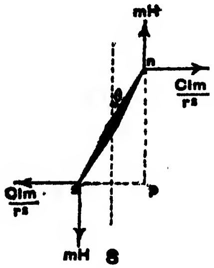


Fig. 103.
Forces acting on needle.

At the same time these poles are urged northward and southward respectively with equal forces 'mH' dynes.

Thus the needle is acted on by two couples in opposite directions, the arm of the first being np ($=sn\cos\theta$), and the arm of the second sp ($=sn\sin\theta$). The needle is in equilibrium, therefore the *moments* of these couples are equal (MECHANICS, p. 65).

$$\therefore \quad \frac{Clm}{r^2} \times sn\cos\theta = m\mathrm{H} \times sn\sin\theta,$$

$$\therefore \quad \mathrm{C} = \frac{\mathrm{H}r^2}{l}\tan\theta.$$

The fraction $\frac{\mathrm{H}r^2}{l}$ contains only the quantities H, r and l, which are always the same for the same instrument, we may therefore calculate its value once for all and denote it by another symbol, say G, which is called the 'galvanometer constant': we then have

$$\mathrm{C} = \mathrm{G}\tan\theta.$$

The current is proportional to the tangent of the angle of de-

flection, and for this reason the instrument is called the Tangent Galvanometer.

Example. — In a Tangent Galvanometer the radius of the ring = 12 cm.; the length of wire acting on the needle = 35 cm.; H = ·18. (1) Find the constant G. (2) What current produces a deflection of 45°? (3) What current a deflection of 30°?

(1) $$G = \frac{Hr^2}{l} = \frac{\cdot 18 \times 12^2}{35} = \cdot 74.$$

(2) $$C = \cdot 74 \tan \theta$$
$$= \cdot 74 \tan 45° = \cdot 74 \text{ C.G.S. units}$$
$$= 7 \cdot 4 \text{ Ampères.}$$

(3) $$C = \cdot 74 \tan 30°$$
$$= \cdot 74 \times \frac{1}{\sqrt{3}} = \cdot 427 \text{ C.G.S. units}$$
$$= 4 \cdot 27 \text{ Ampères.}$$

Reflecting Galvanometer.—In attempting to measure small currents, two difficulties present themselves in the instruments described so far.

Firstly, the friction between the needle and its pivot, although slight, is too great to be overcome by the very minute force exerted by the current; and secondly, even if the needle do move, it is difficult to measure accurately a very small deflection.

These difficulties are overcome in Sir W. Thomson's (Lord Kelvin's) Reflecting Galvanometer. In this instrument the coil is built with a very fine wire taking about 1000 turns, so that the force exerted by the current is multiplied about a thousand times. The needle is replaced by two or three pieces of magnetised watchspring attached to the back of a very light circular mirror. The mirror is usually from ¼ to ½ inch diameter and is of the thinnest glass obtainable—a microscope 'cover slip' answers excellently. The mirror with magnets seldom weighs more than one or two grains, it is suspended by a single fibre of cocoon silk, and is protected from draught by being placed in a small brass tube with glass ends. In the best instruments the mirror is now suspended by one of the delicate fibres of quartz

prepared by the ingenious method recently invented by Prof. Vernon Boys; he takes a piece of quartz, such as the 'pebble' used for good spectacle lenses, heats it in the oxyhydrogen flame, and when a portion is fused he draws it out into a thread by means of an arrow fired from a powerful bow.

Frequently the coil is made in two halves CC, an upper and a lower one, as shown in Fig. 104; in this case the mirror, with magnets at back, is placed in the upper coil, and a light wire extends downward from it and carries a set of magnets at the

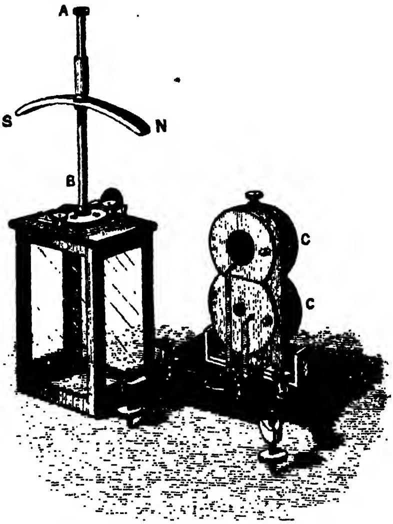


Fig. 104.—Reflecting galvanometer.

centre of the lower coil. The arrangement for reading the deflection is as follows: a horizontal scale A′B′ is fixed on the wooden frame shown in Fig. 105. Immediately under the middle point A′ of the scale is fixed a narrow slit S, through which light comes from the lamp and falls on the mirror M. On being reflected from the mirror, the light in all probability will miss the scale A′B′ altogether, but a careful twisting of the controlling magnet NS, which slides on the upright rod AB (Fig. 104) at the top of the instrument, will bring the spot of

reflected light to the zero point of the scale. Generally a fine vertical wire is fixed in the slit, and a lens placed in front of the slit brings an image of this wire to a sharp focus at A′.

The slit is slightly below the level of the mirror, hence the rays of light passing from S to M are inclined upward, and after reflection they are still inclined upward; hence the scale A′B′ on which the light falls must be slightly above the level of M. A figure representing the rays thus inclined would be confusing; hence in the next paragraph we speak as if the slit were at A and the scale at AB both on a level with M.

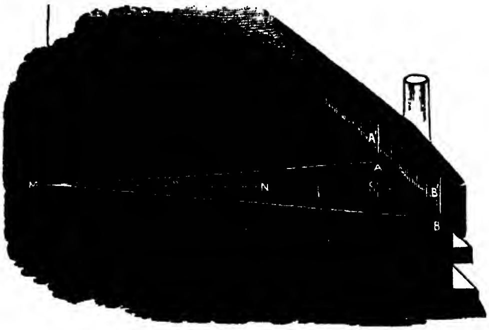


Fig. 105.—Lamp, scale, and mirror for galvanometer.

When the mirror is undisturbed, its normal (*i.e.* the perpendicular to it) coincides with MA; the rays of light from A therefore fall normally on the mirror and are reflected directly back again to A.

If now the mirror be deflected through a small angle α, the normal to it is also turned through an angle α and takes the position MN; and the incident light which was previously normal to the mirror now makes an angle α with the normal; hence the reflected light makes an angle α with the normal on the other side of it, it is reflected along MB, and therefore makes an angle 2α with its original direction MA (see LIGHT, p. 525).

A movement of the spot of light on the scale through 1 mm. can easily be detected, and as the mirror is generally about 2

metres distant from the scale, it is obvious that a very minute deflection of the mirror can thus be detected.

[With the data just given $\tan 2a = \frac{1 \text{ millimetre}}{2 \text{ metres}} = \cdot 0005$, whence by the mathematical tables $a = 52''$ approximately.]

Ammeter.—For use in electric lighting and other branches of electrical engineering special galvanometers called *Ammeters, i.e.* ampère-meters, are constructed. Their coils are usually made of very thick wire so that a strong current can be sent through them without undue heating: and they are provided with a scale graduated so that the pointer indicates directly the number of ampères passing through the instrument.

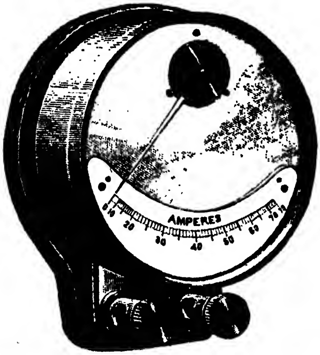


Fig. 106.—Ammeter.

Fig. 106 represents a typical ammeter.

Voltmeter. — This also is a special form of galvanometer used in electrical engineering. The coil of a voltmeter is wound with a long fine wire of high resistance, so that when it is connected to the terminals of a dynamo or battery only a very small current passes through the instrument, and therefore no appreciable effect is produced on the current which passes through any other apparatus or lamps which also are connected to the dynamo.

The current which passes through the instrument is—by Ohm's Law—proportional to the difference of potential of its terminals: hence if the scale be suitably graduated, the deflection of the needle will give directly the difference of potential measured in volts.

And in the same way, if the terminals of the voltmeter be connected to any two points of any electric circuit, the deflection gives the number of volts in the difference of potential between these points.

Cardew's Voltmeter is of special interest from the fact that

the current passing through a fine wire is measured by the expansion caused by the heat which the current produces in the

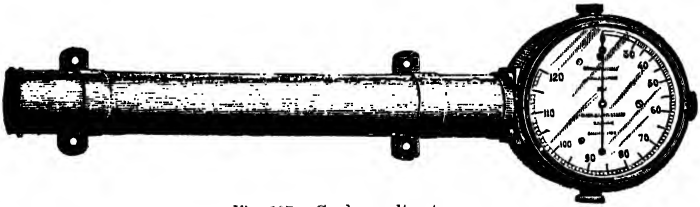


Fig. 107.—Cardew voltmeter.

wire, instead of being measured by the deflection of a magnetic needle.

The wire WW, whose expansion measures the current passing through the instrument (and therefore indirectly measures the difference of potential at its terminals), is attached to two metal pillars P from which stout curved rods lead to the terminals T, T: the wire passes under two fixed pulleys at the end of the tubular casing, and over a loose pulley C at its middle point. A fine thread is fastened to the pulley C and, after passing completely round the small wheel G, is attached to the spiral spring V. When the wire expands, the pull of the spring causes the pulley C to rise and 'take up the slack'; the thread passing round G causes it to turn, and this movement is transmitted to the pointer by the multiplying wheels R and S.

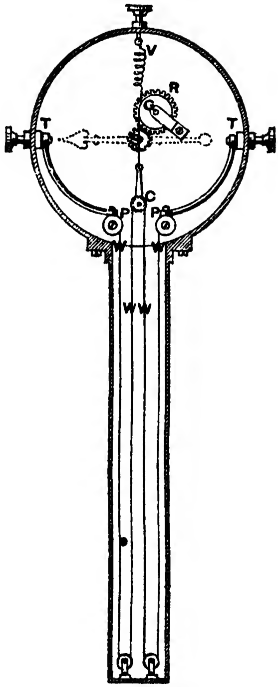


Fig. 108.—Interior of Cardew voltmeter.

Ohm's Law.—On p. 724 we explained in a general way the meaning of the term 'resistance' as used in electricity, and

pointed out that with an increased resistance in a circuit the current must decrease unless the electromotive force be also increased. We further find that the current which flows in any given wire is proportional to the difference of electric potential (*i.e.* difference of electric pressure) at its extremities.

Experiments on the resistance of wires led Ohm to announce his famous law that:—

"The current which flows in any circuit is equal to the electromotive force divided by the total resistance of the circuit," or, "The current which flows in any wire is equal to the difference of potentials of its two extremities divided by its resistance."

The law in its two forms may be represented in symbols thus:

$C = \frac{E}{R}$ where E is the E.M.F and R is the Resistance of the circuit.

or

$C = \frac{V_1 - V_2}{R}$ where V_1, V_2 are the potentials at the two ends of a wire whose resistance is R.

If several batteries or dynamos are included in a circuit, their E.M.F.s being E_1, E_2, E_3, etc., and their internal resistances, r_1, r_2, r_3, etc., we may write the first equation in the form

$$C = \frac{E_1 + E_2 + E_3 + \ldots}{R + r_1 + r_2 + r_3 + \ldots},$$

R being the resistance of the circuit external to the batteries.

Measurement of Resistance.—For the practical measurement of resistance, boxes are constructed in which are conveniently arranged wires of resistance 1, 2, 3, 4, 10, 20, 30, 40 and so on up to 4000 ohms. These wires before being placed in the boxes are carefully compared with standard coils; they are covered with silk to insulate them; they are folded double so that currents flowing through them may have no direct effect on instruments placed near to them; they are then embedded in paraffin wax to protect them from damp or injury.

The manner of using a 'resistance box' is shown in the diagram Fig. 109. A, B, C are blocks of brass fitted on the ebonite cover of the box. The ends of a 1-ohm coil are shown attached to A and B, those of a 2-ohm coil to B and C, and so

on. A current arriving at the terminal T has to pass through the 1-ohm coil from A to B, then through the 2-ohm coil from B to C. In the gap between C and D is firmly wedged a brass plug P (with small ebonite handle). This affords a short cut for the current from C to D, and the resistance of the 3-ohm coil is thus avoided. If plugs be inserted in all the gaps, the resistance of the box from terminal to terminal is practically zero, for the resistance of the brass blocks and plugs is negligible. If selected plugs be then pulled out, any required resistance

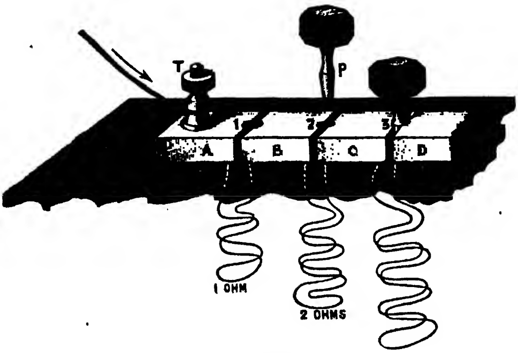


Fig. 109.—Resistance coils.

may be obtained. Thus to obtain 257 ohms we take out the plugs numbered 200, 40, 10, 4, and 3.

Simple Method.—If we wish to ascertain the resistance of a given wire we may arrange it, as at PQ in the diagram (Fig. 110), in series with a galvanometer G in the circuit of a battery B: having observed the galvanometer deflection, remove the wire and insert a 'resistance box' between P and Q; then pull out the plugs until the galvanometer has the same deflection as before. Then the number of ohms indicated by the plugs removed is the resistance of the wire. But the E.M.F. and internal resistance of the cell change between the two observations and make the result inaccurate.

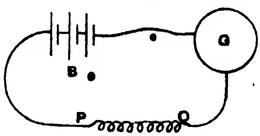


Fig. 110.—Simple method of measuring resistance.

The Rheostat, invented by Wheatstone (1840), was an adjustable resistance, provided by winding more or less of a uniform wire on to an insulating barrel; this he used for measuring resistances, but it was discarded as inaccurate. The term is now widely used of an adjustable resistance to be placed in a circuit to adjust current or voltage, not for measurement. Two main forms of Rheostat are in use—(1) a wire of German silver or of some material the resistance of which does not alter much with change of temperature, tapped at intervals by contact pieces; (2) the "sliding wire," used in automatic recorders.

Numerical Illustrations of Ohm's Law.

(1) A battery of 5 cells, each of E.M.F. 1·05 volt and internal resistance ·1 ohm, is connected 'in series'; the resistance of external circuit is 10 ohms: required to find the current and the distribution of electric potential.

$$\text{Total E.M.F. of battery} = 1{\cdot}05 \times 5 = 5{\cdot}25 \text{ volts.}$$

$$\text{Total resistance of circuit} = \underset{\text{External.}}{10} + \underset{\text{Internal.}}{5 \times {\cdot}1} = 10{\cdot}5 \text{ ohms,}$$

$$\therefore \text{ current} = \frac{5{\cdot}25}{10{\cdot}5} = {\cdot}5 \text{ Ampère.}$$

Now $$V_1 - V_2 = CR,$$

$$\therefore \text{ difference of potential at the ends of wire} = {\cdot}5 \times 10 = 5 \text{ volts.}$$

That is, 5 volts out of the total 5·25 are employed in driving the current through the wire, and the remaining ·25 volts in driving it through the battery (*i.e.* ·05 volt for each cell). The information we have so far obtained deals only with the *difference* of potentials of different points, and tells us nothing of the absolute potential of any point. Now if *any one* point P of the circuit be connected to the earth by a wire PE there may be a momentary rush of electricity from P to the earth or *vice versâ*, if the potential of P happen to differ from that of the earth; but the potential of P will instantly become equal to that of the earth, and no current

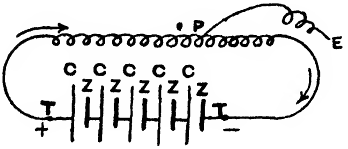


Fig. 111.—Diagram of circuit.

can flow permanently along PE, because there is no path for such a current back from the earth to P.

Now the potential of the earth is zero, hence the wire PE has reduced the potential of P to zero without in any way disturbing the current flowing in the circuit. As a rule it is convenient to imagine that the negative terminal of the battery is connected to the earth by a wire such as PE, and therefore that the potential of the negative terminal is zero.

In the above example the potential at one end of the wire is 5 volts higher than that at the other; therefore if the potential of the negative terminal (− T) be zero, that of the positive terminal (+ T) is 5 volts.

In passing through the battery from − T to + T we might

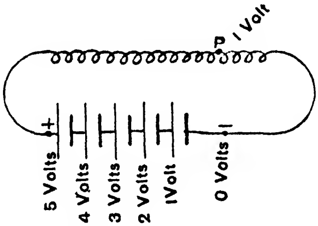


Fig. 112.—Distribution of potential in circuit.

expect the potential to rise 1·05 volt as we pass through each cell—for the E.M.F. of each cell is 1·05 volt. But if we remember that ·05 volt is used to drive the current through the cell, we see that the actual rise of potential per cell is 1·05 − ·05, that is 1 volt.

If the wire be of uniform diameter and length 50 feet, then considering a point P, 10 feet from − T, the resistance from P to − T is 2 ohms ($\frac{10}{50}$ of 10 ohms).

$$\therefore \text{ Difference of potential between P and } -\text{T} = \text{C} \times \text{R} = \cdot 5 \times 2 = 1,$$
$$\therefore \text{ Potential of P} = 1 \text{ volt.}$$

Similarly we can find the potential of any other point of the wire.

(2) Two wires, of length 30 ft. and 50 ft., and resistance

6 ohms and 10 ohms, have their ends twisted together at A and B. These joints are connected to the terminals of a battery which keeps A at a potential 10 volts when B is at potential 0: find what currents flow.

$$\text{Current through the 6-ohm wire} = \frac{V_1 - V_2}{R} = \frac{10}{6} = 1\tfrac{2}{3} \text{ ampère.}$$

$$\text{Current through the 10-ohm wire} = \frac{V_1 - V_2}{R} = \frac{10}{10} = 1 \text{ ampère.}$$

Hence the current along DA, which splits up at A into these two branches, must be $1 + 1\frac{2}{3} = 2\frac{2}{3}$, and the current along BE, their reunion, is also $1 + 1\frac{2}{3} = 2\frac{2}{3}$ ampères.

(3) What is the resistance of the single wire inserted between A and B which would allow the same total current to pass?

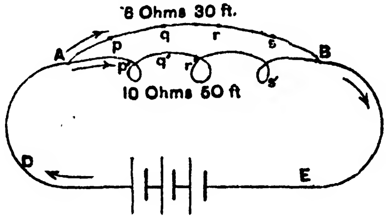


Fig. 113.—Resistances in parallel.

$$\text{Required resistance} = \frac{V_1 - V_2}{C} = \frac{10}{2\frac{2}{3}} = \frac{30}{8} = 3\tfrac{3}{4} \text{ ohms.}$$

Hence two resistances, 6 ohms and 10 ohms, placed 'parallel' as above, are equivalent to a single resistance of $3\frac{3}{4}$ ohms.

[It is easy to see that in general if a single resistance R be equivalent to R_1 and R_2 placed 'in parallel,' then—

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}, \text{ and } \therefore R = \frac{R_1 R_2}{R_1 + R_2}.$$

If R_1 and R_2 be placed 'in series,' obviously their equivalent resistance is $R_1 + R_2$.]

(4) If we divide the 30-foot wire into five equal parts, each will be 6 feet long, and will have a resistance $\frac{6}{5}$ ohm. The difference of potential required to drive a current $1\frac{2}{3}$ ampère through $\frac{6}{5}$ ohm is $1\frac{2}{3} \times \frac{6}{5} = 2$ volts. Hence as we go up-current

along the wire from B to A, the potential rises 2 volts in each of the 6-foot sections.

Similarly dividing the 50-feet wire into five equal parts, each is 10 feet long and has a resistance 2 ohms, and since the current in this wire is 1 ampère, the potential rises $1 \times 2 = 2$ volts in each of the 10-feet sections.

It is easy to see that whatever number of equal sections be taken in the two wires the rise of potential will be equal in each section, and hence to see that the potential rises uniformly from B to A along either wire.

This fact is represented graphically in the diagrams (Fig. 114).

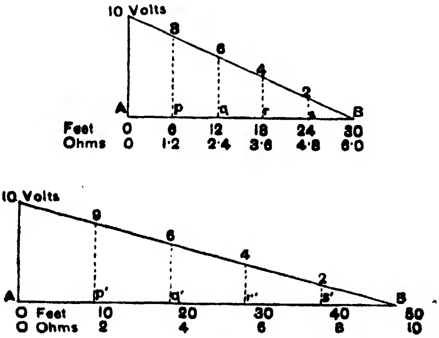


Fig. 114.—Distribution of potential, wires in parallel.

In these the horizontal lines represent lengths of wire measured from A, they also represent the number of ohms resistance of the wire measured from A, and the vertical height at any point represents the potential at that point.

Note that the points q and q', each at $\frac{2}{5}$ of the whole distance from A to B, are at the same potential: hence if wires leading to a galvanometer be connected to q and q', no current will flow along them, and the galvanometer will show no deflection.

Wheatstone Bridge.—The preceding illustrations should make it easy to understand the method of measuring resistance invented by Wheatstone, and named after him the Wheatstone Bridge method.

The requisite arrangement of apparatus is given in Fig. 115: R_1 and R_2 are coils or boxes of known resistance usually 10, 100, or 1000 ohms. R is a box whose resistance can be varied at will by inserting or taking out plugs as described on p. 787; x is the wire, coil, cable, etc., whose unknown resistance we wish to measure.

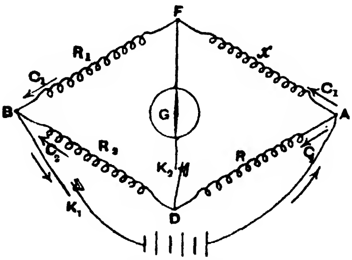


Fig. 115.—Diagram of Wheatstone bridge.

These four resistances R_1, R_2, R and x are connected end to end at F, B, D, A. Wires from a battery are connected to A and B; wires from a galvanometer are connected to F and D; a key K_1 is placed between the battery and B, and another key K_2 is placed between D and the galvanometer.

When the key K_1 is depressed a current flows from the battery to A, there it splits into two branches, one C_1 flowing along AFB and the other C_2 along ADB. At B these branches reunite and flow back to the battery.

If the galvanometer key K_2 be now depressed, a current will flow through the galvanometer unless F and D are at the same potential. The measurement is made by adjusting the resistance R until the galvanometer gives no deflection when the key K_2 is depressed.

We then have, if V_A be the potential of A, V_B the potential of B, and V the potential of F and also of D—

$$V_A - V = \text{difference of potential at ends of } R = C_2R,$$

also $$V_A - V = \text{difference of potential at ends of } x = C_1x,$$

$$C_1x = C_2R.$$

Similarly $$C_1R_1 = C_2R_2,$$

$\therefore$ by division $$\frac{x}{R_1} = \frac{R}{R_2},$$

$$\therefore x = \frac{R_1}{R_2} \cdot R.$$

The superiority of this method of resistance-measuring is due to

the fact that it is far more easy to detect a minute deflection than it is to read accurately any considerable deflection: hence it is possible to adjust the resistance R with great nicety until there is an exact 'balance' between R_1, R_2, x and R, for a very slight error in balancing can be detected by a minute current through the galvanometer.

Post-Office Box.—For convenience of working it is usual to combine the resistances R_1, R_2 and R in one box, which often is

Fig. 116.—Post-Office box.

also fitted with the keys K_1K_2 to be used for the battery and the galvanometer. The form known as the 'Post-Office Box' is shown in Fig. 116. The arrangement of the resistances is shown separately in plan in Fig. 117, in which the letters are inserted to correspond with the bridge in Fig. 115.

Clearly it is of no importance in which direction the currents C_1C_2 flow along the branches AFD, ADB, since we only require

to adjust the resistance R until no current flows through the galvanometer.

Callendar's Electric Resistance Thermometers.—The essential part of these instruments is a fine platinum wire, whose resistance becomes greater as its temperature rises. This is

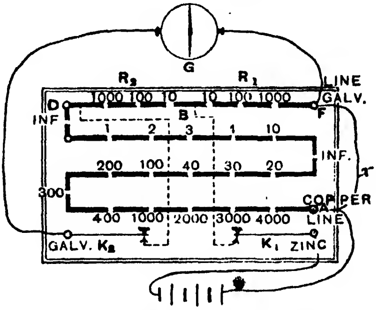


Fig. 117.—Plan of Post-Office box.

wound on a mica frame and connected by stouter wires with an indicator or recorder, consisting of an arrangement including a resistance box, or rheostat, by which the resistance of the fine wire is measured and its temperature estimated. These thermometers are made by the Cambridge Scientific Instrument Company in forms adapted for reading temperatures from the lowest up to near the melting point of platinum (1700° C.).

Langley's *Bolometer* (pp. 395, 603) is a resistance thermometer.

Specific Resistance and Conductivity

(From Lupton's Tables, by permission.)

The specific resistance of a substance is the resistance at 0° C. between opposite faces of a cube of it which measures 1 cm. each way. The conductivity of a substance is the reciprocal of its resistance.

R. in Microhms.[1]

Metals.	Resistance.	Conductivity.
Silver, hard drawn	1·609	·621
Copper ,, ,,	1·642	·609
Gold ,, ,,	2·154	·464
Platinum, annealed	9·158	·109
Iron, soft	9·827	·102
Tin, pressed	13·36	·075
Lead ,,	19·847	·050
Mercury	94·34	·010

[1] A Microhm is a millionth of an ohm.

CHAPTER VIII

Effects produced by Current

Heating Effects—Incandescent Lamps—Amount of Heat Produced—Safety Fuse — Explosive Fuse — Thermo-electricity—Its laws — Thermopile — Electric Arc—Arc Lamp—Discharge through Rarefied Gases—Geissler Tubes—Crookes' Radiant Matter—Röntgen Rays—Radium.

Heating Effects.—We have seen that frictional electricity when passing through a wire heats it slightly, the same effect is produced in a much more powerful manner by currents from batteries or dynamos. Thus, if a battery of five or six Grove cells be connected to a fine iron wire (such as is used for making up buttonholes) about a foot long, the wire immediately becomes red hot, then white hot, and if the battery be in good condition, the wire will melt, scattering little globules of molten iron in all directions.

By experimenting with various wires, we find that with the same current thick wires become less heated than fine ones, and that materials of high resistance become more heated than good conductors of the same diameter. This may be illustrated by a pretty experiment: a chain is made with alternate links of silver and platinum; silver and platinum being of the same colour, the eye scarcely detects any difference between the links, but when a current is passed through the chain and gradually increased, the platinum links become red-hot and visible in the dark, while the silver links are scarcely warmed; this is because the specific resistance of platinum is about six times that of silver.

By using the current from a big dynamo, or from four or five secondary batteries connected 'in parallel,' an iron rod a quarter of an inch in diameter may be made white hot.

Incandescent Electric Lamps.—The fact that wires become white hot by the passage of a suitable current has been utilised in electric lighting by the construction of incandescent or glow lamps. In the earliest glow lamps a platinum wire was used, but the resistance of platinum was not sufficient to enable light

Fig. 118.—Incandescent lamp.

to be produced with an economical current; in 1879 and 1880 Edison and Swan independently invented lamps in which the platinum wire was replaced by a fine thread or 'filament' of specially prepared carbon; the filament is made from a fibre of bamboo, strip of paper or fine cotton, it is first treated with dilute sulphuric acid (2 parts water to 1 acid), then 'carbonised' by being heated in a muffle furnace; after being carefully rounded, hardened, and polished, the filament is

cemented to two short platinum wires which are sealed into the well-known little glass globe. Before sealing the point the globe is connected to a mercury air-pump (HYDROSTATICS, p. 179) and all the air exhausted from it.

If a carbon filament were heated to whiteness in the air it would be immediately burned up, its carbon combining with the oxygen of the air; hence it is necessary to produce the best possible vacuum in the globe, so that there may remain no trace of oxygen to combine with and burn up the carbon.

A good incandescent lamp of say 16 candle power requires a current of about $\frac{1}{2}$ ampère, its resistance when hot is about 200 ohms, and hence the E.M.F. it requires is about 100 volts.

Filaments of the metals tantalum and tungsten are taking the place of carbon filaments; these are so fine that they are more fragile, but, for the same candle power, they are more economical in current, using only 1 watt per candle power.

Amount of Heat Produced.—Both Joule and Favre made a set of experiments to determine the *amount* of heat produced in any wire, and found it to be proportional to the resistance, also proportional to the square of the current, and of course proportional to the time during which the current flows.

Joule proved that a current C flowing through a resistance R for a time t produces an amount of heat which is mechanically equivalent to C^2Rt ergs of work; here the current and resistance are measured in absolute C.G.S units, hence remembering that 1 ampère $= \frac{1}{10}$ C.G.S. unit, and 1 ohm $= 10^9$ C.G.S. units, the heat is equivalent to 10^7C^2Rt ergs, where C is measured in ampères and R in ohms.

Now in HEAT, p. 370, we saw that 1 gramme-centigrade unit of heat is equivalent to $10^7 \times 4{\cdot}2$ ergs,

$$\therefore \left.\begin{array}{l}\text{the heat produced by a current} \\ \text{C ampères flowing for } t \text{ sec.} \\ \text{through R ohms}\end{array}\right\} = \frac{10^7C^2Rt}{10^7 \times 4{\cdot}2} = \frac{C^2Rt}{4{\cdot}2} \text{ (gramme-centigrade units).}$$

Ex.—If the above described incandescent lamp be immersed in 250 grammes of water for 10 minutes, and give up all its heat to the water, how much will the temperature of the water rise?

$$\left.\begin{array}{r}\text{Heat produced in}\\ \text{600 seconds}\end{array}\right\} = \frac{(\cdot 5)^2 \times 200 \times 600}{4\cdot 2} = \frac{30000}{4\cdot 2} = 7140 \text{ units},$$

$$\therefore \left.\begin{array}{r}\text{temperature of}\\ \text{250 grammes}\end{array}\right\} \text{ rises } \frac{7140}{250} = 28\cdot 5 \text{ degrees Centigrade.}$$

Safety Fuse.—This is a short length of easily fusible wire (an alloy of tin and lead) which is placed in the circuit of each lamp or group of lamps, its thickness being selected so that it will carry the normal current of the circuit, but melt if an excessive current passes. It would be difficult in practice to adjust a fuse to this degree of accuracy, and owing to the small fluctuations in a modern lighting circuit it would generally be unnecessary to use one. A fuse, however, is always placed in any circuit of lamps or machinery to prevent damage or fire, in case of short circuit. The fuse should be in an accessible place, so that a fresh length of the fusible wire can easily be slipped into position.

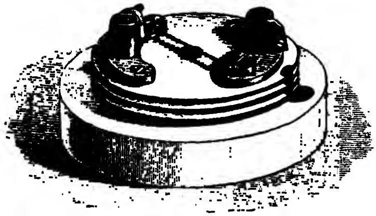


Fig. 119.—Safety fuse.

Explosive Fuse.—Electric fuses are also used for firing submarine mines, torpedoes, etc.; in these a short length of fine platinum wire is embedded in fine gunpowder; when a current is passed, the platinum becomes white hot and ignites the powder.

Thermo-electricity.—In 1821 Seebeck found that when two wires of different materials are twisted or soldered together at their ends so as to form a complete circuit and one of the junctions is heated, an electric current flows in the circuit; and that, if the junction be cooled, a current also flows but in the reverse direction. Such currents are called thermo-electric. Fig. 120 is a simple apparatus for showing this; the copper and iron bars forming the circuit are riveted or soldered together at each end, the frame is placed magnetic north and south, so that the needle N.S. lies parallel to the bars. When the right-hand junction is heated, the needle is deflected and indicates a current flowing from copper to iron through the hot junction. If the

left-hand junction be gradually heated as well as the right-hand, an E.M.F. is produced opposing that produced on the right, so that the current diminishes, and finally disappears when both junctions are at the same temperature.

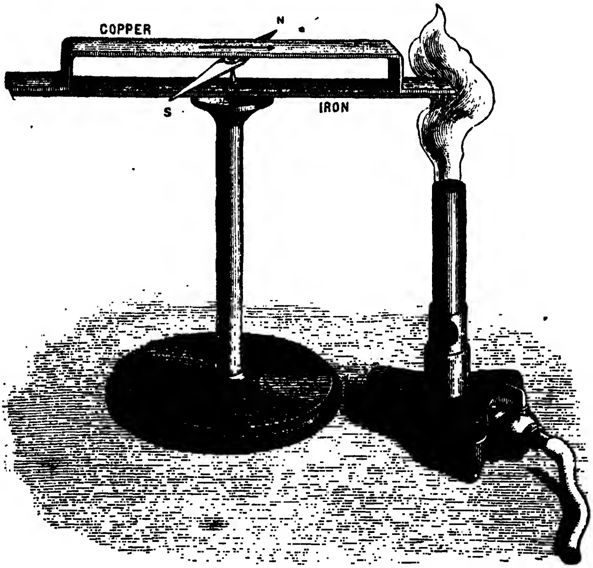


Fig. 120.—Thermo-electric junction.

The effect is also shown if a copper and an iron wire be twisted together at one end, while the other ends are taken to a galvanometer (Fig. 121); when the junction is heated, the galvanometer shows an E.M.F. from copper to iron.

If several pieces of wire, alternately copper and iron, be twisted together at their ends, and all the left-hand junctions be heated, the right-hand ones being maintained cool, the E.M.F. at each hot junction pushes in the same direction round the circuit, and we have an increased effect, just as when several Voltaic cells are connected in series. If both right-hand and left-hand junctions be heated the opposing E.M.F.s soon reduce the current to zero. Other metals may be used in place

of copper and iron, and it is found that an antimony-bismuth pair gives the best results.

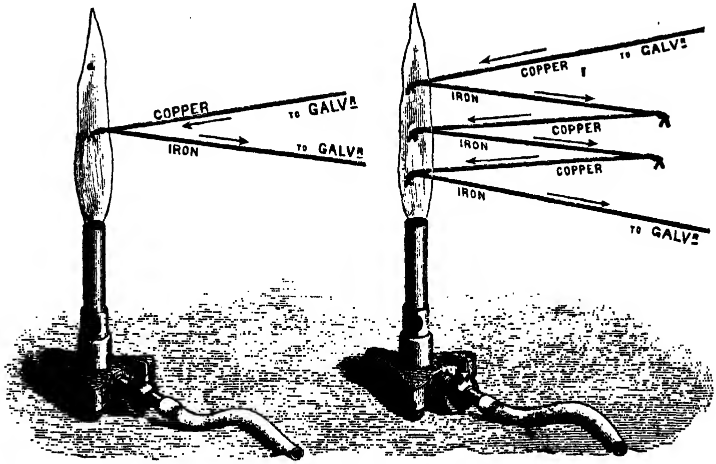


Fig. 121.—Thermo-electric junctions.

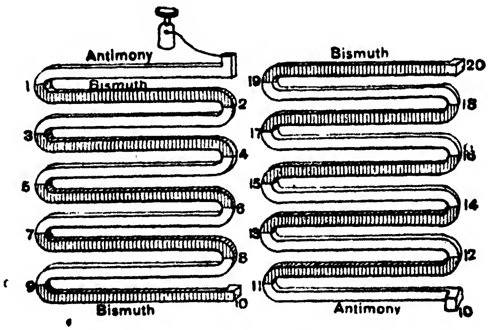


Fig. 122.—Junctions in Nobili's thermopile.

Laws of Thermo-electricity.—The following laws are found to be true for a two-metal circuit—

(1) The thermo-electromotive force is proportional to the difference of temperature of the junctions, so long as the mean temperature of the two junctions remains the same, *e.g.*:—

(*a*) Junctions at 40° and 60° (mean temp. 50°), we have a certain E.M.F. belonging to the difference 20° in temperature.

(*b*) Junctions at 20° and 80° (mean temp. 50°), we have three times the previous E.M.F., for the difference of temperature is now 60°.

(2) With a given difference of temperature of the junctions, the thermo-electromotive force is proportional to the *difference* of their *mean temperature* from a certain temperature called the *neutral point;* each pair of metals has its own fixed neutral point. For iron and copper it is about 260° C.

(*a*) Junctions of iron and copper at 40° and 60°:—difference of temperature 20°; the mean temp. 50° is *210° below neutral point.*

(*b*) Same junctions at 180° and 200°:—difference of temperature 20° (as before); the mean temp. 190° is *70° below neutral point;* hence we have only one-third the previous E.M.F.

(*c*) Same junctions at 250° and 270°:—difference of temperature 20° (as before); the mean temp. is 260°, which is the neutral temperature; hence there is no E.M.F.

Thermopile.—A thermopile is a compact arrangement of several thermo-electric 'pairs,' grouped so that alternate junctions can be heated or cooled. Some years ago Clamond designed a thermopile intended to take the place of a battery, its alternate junctions were arranged in rings round a big Bunsen burner; this thermopile did not answer very well, and soon dropped out of use, but it was interesting as an attempt to convert heat energy direct into electric energy, and to utilise it as such.

However, the thermopile has proved extremely useful* in another field, namely, in the detection of minute differences of temperature. Nobili's pile is adapted for this purpose; in it square rods of antimony and bismuth, 7 or 8 cm. long, are soldered together into a vertical strip (Fig. 122); they must

be carefully insulated so as only to touch each other at the junctions. Several of the vertical strips are connected together and placed in a frame, so that all the even numbered junctions are at one end and the odd at the other.

Terminals are attached to the first antimony and the last bismuth rod, and wires are led from them to a delicate galvanometer: so sensitive is this thermopile that the heat given out by a match lighted 100 feet or more away from it is readily detected. A complete thermopile is shown at A in Fig. 123, it

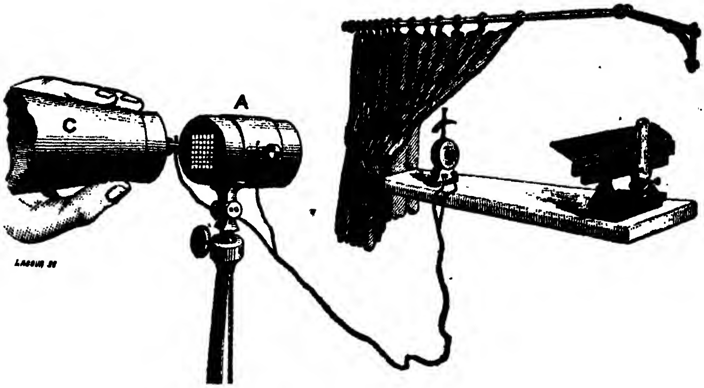


Fig. 123.—Nobili's thermopile.

is there connected up to a reflecting galvanometer on a distant shelf. In this instrument there are six vertical strips, each having 14 junctions, the 42 junctions at one end of the pile appear as a square patch on the face presented to us in the figure; C is a long conical tube which protects the face of the pile from any heat arriving from any direction other than that in which the cone points.

The Electric Arc.—If two carbon rods be connected to the terminals of a dynamo or of a powerful battery (say 20 Grove cells or secondary cells), and if the ends of the rods be gradually brought near to each other, no current is able to pass when they are as near as $\frac{1}{8}$ inch or even at $\frac{1}{1000}$ inch; but if once the

carbons be allowed to touch, a current passes, and if they then be drawn apart about $\frac{1}{8}$ inch, the current continues to pass, forming an 'arc' of light across the gap; the heat of this 'arc' is intense, hence the ends of the carbon rods become brilliantly white hot, emitting a light of high candle power. Submitted to this temperature the carbons burn away, but not both at the same rate; the positive carbon (*i.e.* the one from which the current flows) burns twice as fast as the negative: the reason for this appears to be that particles of incandescent carbon are torn away from each rod, and are carried from one to the other, and that the greater number of the particles travel with the current. A further result from this is that the positive carbon gets hollowed out into a crater, while the negative one becomes conical, as seen in Fig. 125. The heat of the electric arc is used in electric furnaces for welding steel, making carborundum, etc.

In Fig. 124 we give a picture of two fluted carbons sketched after actual use in the St. Catherine's Lighthouse, Isle of Wight. This lamp, now (1907) used at the South Foreland, has an illuminating power estimated at 50,000 candles, when supplied with a current of 400 ampères. Now the passage of such a current as this through even a metallic conductor of moderate dimensions would produce an appreciable rise of temperature, hence, seeing that the electrical resistance of prepared carbon is about two thousand times as great as that of copper, it will easily be understood that an ordinary round carbon 40 millimetres ($1\frac{9}{16}$ in.) in diameter would be rendered red hot by this current. To avoid this undue heating the outside diameter of the carbons is increased to 60 millimetres ($2\frac{3}{8}$ in.), and the carbons are moulded with the deep flutings shown in the figure; this provides a much larger cooling surface than a round carbon of the same diameter, and by thus dissipating the heat rapidly, it keeps the temperature down to a reasonable point.

Fig. 124.
Fluted carbons.

Since an alternating current has been used with these carbons the end of each is formed into a hollow crater. The fluting of the carbons tends to keep the arc in the centre of the carbons and to prevent it from flickering from side to side. These carbons, moreover, have a central core of softer carbon, which burns away more easily than the harder flutings, and thus helps to keep the arc in the centre.

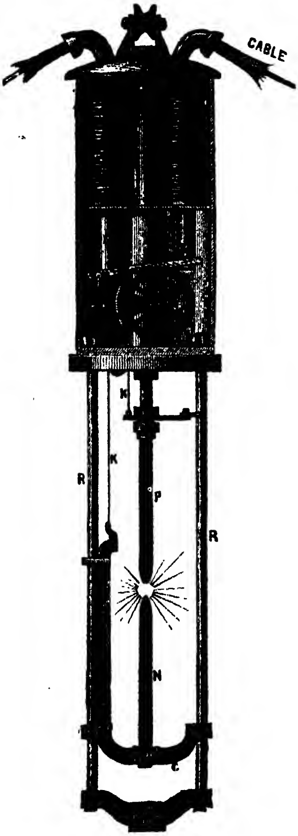


Fig. 125.—Arc lamp.

Arc Lamp. — In utilising the arc for electric lighting the chief difficulties are (1) separating the carbons immediately the current starts, (2) regulating the distance between the carbons, so that, as they burn away, the arc may always be the same length. The 'hand regulator' or 'hand lamp' is the simplest; in it the carbons are placed in holders, adjusted by racks and pinions worked by hand: this form is still generally used for naval search lights.

Automatic arc lamps must be used for street lighting, for it would hardly pay to have a man at each lamp-post to keep the light going. Different devices are used by different makers—Brush, Crompton, etc. We will briefly describe the Brockie Pell Lamp, which is shown in section in Fig. 125. The current on arriving from the cable is led round the electromagnet M, which is wound with thick wire; from M the current passes to the positive carbon P by way of the metal rod into which it is clamped and the metal guides between which this rod slides; from the

positive carbon the current makes its way through the arc to the negative carbon N, and thence through the guide rods RR to the negative terminal, from which the cable conducts the current on to the next lamp.

A light cord or chain KK passing over a pulley connects the holders of the + and − carbons, so that whenever P descends N ascends to meet it; of course a block of some insulating material must be placed at one end or other of the chain K in order to prevent a 'short circuit' from one holder to the other, and the reader must understand that throughout the lamp due precautions are taken to prevent the current taking any short circuit.

The movement of the carbons is regulated as follows: The vertical rod which constitutes the holder of the positive carbon is formed into a rack, gearing into a pinion which is mounted on the same axle as the brake wheel shown behind B in the figure. When the brake B is lifted, it clutches the wheel and raises the carbon P; when the brake is lowered, it loses its grip on the wheel, and the weight of the positive holder makes it descend, so that the carbons approach one another. The brake is worked by the lever L, to which it is connected by a short link on the left; and the lever is acted on by the moving cores C, *c* of the 'sucking magnets' M, *m*. The electro-magnet *m* is wound with a fine wire to give it a high resistance, and is connected as a 'shunt' across the terminals of the lamp, *i.e.* it is 'in parallel' with the electro-magnet M, the carbons, and the arc: hence M and the arc take the greater part of the current arriving by the cable, while *m* takes only a small fraction of the current; however, the wire on *m* has many more turns than the wire on M, therefore they suck their cores with almost equal force, and the lever is just balanced when the arc is burning well. If the arc becomes too long its resistance increases, hence less current passes through M and the arc, and more through *m*; this increases the pull on *c*, and decreases the pull on C; the brake is lowered slightly, loses its grip, and allows the carbons to approach one another. Conversely, if the arc be too short, C is pulled more

forcibly than c; the brake grips the wheel, rises slightly, and separates the carbons.

The electric arc between two carbons is influenced by a magnetic field in the same way as a wire carrying a current (p. 760). Hence the arc may be 'blown out' into a flame by the repulsion of an electric magnet, or may be controlled by the variations of a magnetic field.

Discharge through Rarefied Gases.—Very beautiful luminous effects are observed when electricity is allowed to discharge through rarefied air or other gas, instead of 'sparking' across an air gap at ordinary pressure.

The 'Electric Egg' (Fig. 126) forms one convenient means of showing these effects: it consists of a glass globe 8 or 9 in. high, cemented below into a brass socket, which can be screwed on to the plate of an air-pump.

A brass rod, ending below in a knob, slides air-tight through the stuffing-box at the top of the globe; a second knob is fixed to the rod below; wires from a Ruhmkorff coil are attached above and below.

Before exhausting the air the knobs must not be separated by more than about half-an-inch, if we wish the spark from an ordinary coil to pass; but as the air is pumped out the distance can be gradually increased, and at the same time the spark quite changes in character; instead of a sharp white flash at each spark, we find at first a luminous column of reddish purple hue extending from knob to knob. As the exhaustion proceeds, and the knobs are further separated, the column splits up into a number of bowed rays of bluish light, flickering about and almost filling the globe; a bright point of purplish light is seen on the positive knob at the starting-point of each ray, while the rays die away at a short distance from the negative knob, and the negative knob itself is surrounded by a somewhat bright blue glow.

Geissler's Tubes also exhibit these effects in a very beautiful way: they are glass tubes often drawn into fantastic shapes, a simple one is shown connected to the Ruhmkorff coil in Fig. 96: at each end a platinum wire is sealed through the glass, and the

air having been pumped out as far as possible by means of a Sprengel pump, the tube is hermetically sealed. When the

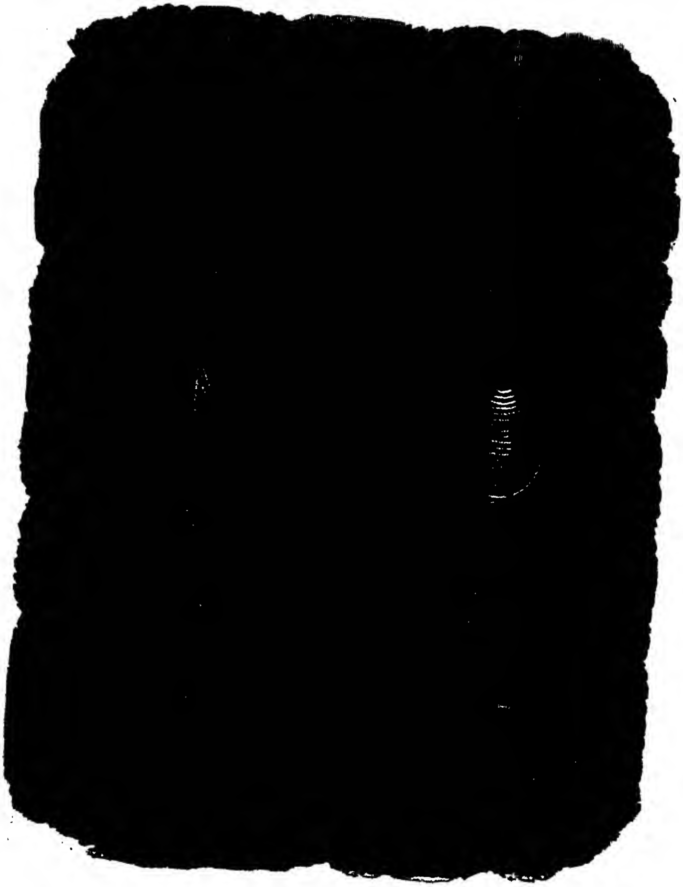


Fig. 126.—Electric egg.

Ruhmkorff coil is connected up to the platinum wires, the discharge passes from one platinum point to the other through the tube; delicate wavy bands of light, called striæ, with dark

spaces between them, are observed in the tube when the exhaustion has been carried to a certain point. This effect in the Electric Egg is shown in Fig. 126 on the right. If before exhaustion different gases be admitted into the tubes, so that a trace of gas remains within them at the time of sealing, variations are observed in the colour of the glow; thus, with hydrogen, the glow throughout the tube is a delicate mauve, but changes to crimson in parts where the tube is narrow; with nitrogen, the violet glow surrounding the negative pole is very bright, while throughout the tube a rosy hue prevails.

Portions of the tubes are frequently made of glass containing uranium, which is almost colourless when exposed to ordinary

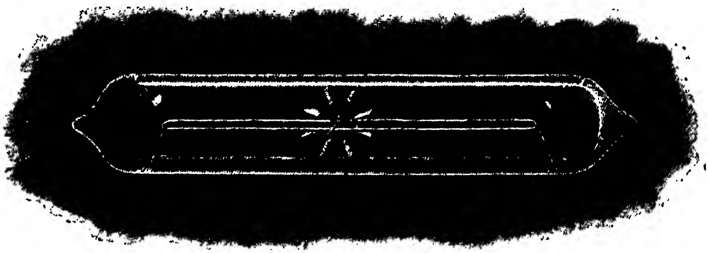


Fig. 127.—Crookes' radiant matter tube.

light, but 'fluoresces' with a delicate green colour when the discharge passes through the tube.

Crookes' 'Radiant Matter.'—Crookes greatly improved the methods of exhausting Geissler tubes, and proved that when a very 'high' vacuum is obtained, a 'something' radiates in straight lines from the negative terminal: he called this something *radiant matter*, for it seems probable that it actually consists of a stream of negatively charged molecules of gas projected in straight lines from the terminal. Among the various ingenious methods employed by him to illustrate this, he contrived in an exhausted tube a light paddle wheel, which is rotated by the stream of 'radiant matter' directed on its paddles. Such a tube is shown in Fig. 127.

Röntgen Rays.—The rays, whether of light, of matter, or

of electric action, emanating from the negative terminal (*i.e.* the cathode) of a vacuum tube have long been known as 'cathode rays.' The German physicist Lenard experimented on the photographic action of these rays a few years back; but the sensational discovery that there are radiations excited by a Crookes' vacuum tube, by which it is possible to produce a photograph of the living skeleton, was reserved for another German physicist. Prof. W. C. Röntgen of Würzburg discovered mysterious rays, which he named 'X-rays,' emanating from a Crookes' tube. These X-rays, he found, could pass through wood, cardboard, flesh and many other substances, which are quite opaque to ordinary light. Most metals proved to be opaque to the rays, although when very thin sheets of metal were placed in their path, the rays passed through them to a limited extent, depending on the metals used. Aluminium proved to be very transparent to the X-rays, allowing their passage quite as freely as wood does; bone, ivory, glass, etc., allowed the passage of the rays to a limited extent, being much more transparent than metals, but more opaque than wood or flesh. When we add that the rays act on a sensitive photographic plate and produce in its film the same chemical changes as ordinary light does, it is easy to see how photographs of bones or of needles or bullets embedded in the flesh may be obtained.

A sensitive plate is wrapped carefully in two or three sheets of black paper, so that there is no possibility of ordinary light reaching the film; the hand, for example, is then placed flat on the plate and a Crookes' tube fixed about a foot above the hand. As soon as the Crookes' tube is excited by a Ruhmkorff coil, the X-rays radiating from it fall, some on the hand, some directly on such parts of the black paper as are not covered by the hand; of the rays falling on the hand those which only meet with flesh pass straight through it and then through the paper to the plate; those rays, however, which meet any bone in their path are for the most part stopped by it, hence a photographic shadow of the bones is formed on the plate. When the plate

is developed a negative picture of the bones appears, and positive pictures can be printed from this in the ordinary way.

There is a fundamental difference between the mode of production of an ordinary photograph and an X-ray photograph. Ordinary light is refracted or bent, whenever it passes from air to glass or from glass to air, hence a lens can be used to bring to a focus (LIGHT, p. 556) light which has diverged from any point, and we can form on a screen an image or miniature picture of the objects placed in front of the lens. But up to the present no means of bending X-rays has been discovered; they therefore cannot be brought to a focus, and the picture produced by them is merely a record of the shadow cast by the bones.

Fig. 128.—X-ray focus tube.

For this reason the pictures have been given the uncouth name *Skiagram* (σκία, *skia*, a shadow).

Now just as with ordinary light we get a well defined shadow bordered by only a slight penumbra when the light emanates from a small source of light, such as a small candle flame, but get a confused shadow with a deep fringe of penumbra when the light comes from a large area, such as an opal globe (LIGHT, p. 512), so with the X-rays we obtain the best defined photographs when the rays emanate from a small surface. The 'focus tube' shown in Fig. 128 is designed to give X-rays radiating only from a small area.

It appears that the X-rays do not originate at the cathode itself but at any point where cathode rays strike upon some solid body; moreover, the cathode rays themselves always leave the cathode normally, that is perpendicularly to the

surface—the greater number of rays coming from the side nearer to the anode. Hence if in a Crookes' tube the plate which is used as cathode be flat or convex, the rays from it travel through the tube and the first solid obstacle they ordinarily meet is the glass of the tube itself. The glass then glows with a beautiful greenish yellow fluorescence wherever the cathode rays fall upon it, and X-rays are excited at and radiate from the surface of the glass wherever the cathode rays fall on it. This explains why skiagrams, if taken with an ordinary Crookes' tube, are often ill-defined.

In the so-called 'focus tube' the cathode K is shaped as part of a small hollow sphere, near the centre of which is placed the anode A. Thus the rays emerging from the inner surface of the cathode travel along the radii, and all impinge on the anode instead of on the glass, the anode therefore becomes the seat from which X-rays radiate, and, being comparatively small, it provides well-defined shadows.

The student must not be misled by the name 'focus-tube' into imagining that it affords a means of focusing X-rays in any such way as a lens focuses light-rays, for, as before stated, no way of deflecting an X-ray has yet been discovered; all that the focus tube does is to start the cathode rays in a convenient direction, so that the first solid object they meet is the small anode plate. The anode plate is made of platinum and becomes red-hot after the cathode rays have been falling on it for a few seconds; it is fixed obliquely on its stem, so that the X-rays from it may pass out perpendicularly on one side of the glass bulb, and so fall directly on the object to be studied.

It is very interesting to watch the changes in the character of the discharge in a Crookes' tube if it be kept connected up to a Ruhmkorff coil during the process of exhaustion. The first stages are similar to those in the 'Electric Egg' (Fig. 126). At a certain stage the whole interior of the bulb is filled with a hazy purple light; as the pumping goes on, a dark space begins to form round the cathode; this dark space gradually increases until it reaches the glass of the bulb, the

glass then glows with a yellowish fluorescence wherever the dark space reaches it. Ultimately the purple haze is driven back so far that the dark space completely fills the bulb and the whole of the glass is fluorescent, the fluorescence being most brilliant where the glass is most directly exposed to the cathode rays.

Fluorescence is caused in certain substances, notably barium-platino-cyanide when X-rays fall upon them. A convenient mode of exhibiting this fluorescence is by means of screens covered with a coat of the substance. If any objects be interposed between a focus tube and such a screen, no X-rays fall on the parts of the screen immediately behind those objects which are opaque to the rays, and on such parts of the screen no fluorescence is produced; hence a shadow-outline of the opaque objects is formed on the screen, and constitutes an easily visible picture. In this way the bones and various moving organs of living animals can be seen.

We may note incidentally a striking difference between Crookes' 'radiant-matter-rays' and Röntgen's 'X-rays,' the former can be deflected by a magnet brought near to the tube, but the X-rays show no trace of deflection by a magnet.

Radio-Activity.—The discovery of the X-rays by Röntgen was followed by great activity in the researches into the nature of the electric discharge carried on in the Cavendish Laboratory at Cambridge by Professor J. J. Thomson and his school. At the same time, throughout the world much thought was given to all questions connected with radiation.

In 1896, Becquerel discovered that uranium and all its compounds emit rays which can penetrate thin plates of metal and other substances opaque to ordinary light; these rays act upon a photographic plate; also, if they fall on the air surrounding an electrified body they cause it, as do the Röntgen rays, to lose its charge. Substances which give out such rays are said to be 'radio-active,' and the phenomenon is called Radio-activity.

M. and Mme. Curie (1898-1903) extracted from pitch-blende a substance, radium, which is many thousand times more radio-active than uranium, and which also possesses the startling

property of maintaining its temperature several degrees above that of the surrounding air, and of continuously radiating heat energy without any apparent supply of heat being imparted to it.

The rays emitted by radium are of three kinds—

(1) α-rays, which are positively electrified and which have a very low power of penetrating solids, liquids, or gases.

(2) β-rays, which are negatively electrified and are more penetrating.

(3) γ-rays, which have great penetrating power, passing readily through 1 cm. of lead, are observable even after passing through 12 inches of iron.

α-rays are deflected only very slightly by the most powerful magnetic forces, β-rays are easily deflected by them and γ-rays undeflected.

The study of radio-activity has thrown much light on the nature of electricity, and has also profoundly modified our views as to the character of the chemical 'atom.' It appears that the cathode rays (p. 808), discovered by Crookes in his tubes and described by him as 'streams of negatively charged molecules of gas,' consist of fragments of the ordinary chemical atoms, each being in magnitude about the thousandth part of a hydrogen atom. These fragments are now termed *corpuscles;* each carries a negative electric charge which cannot by any process be abstracted from it, and each carries exactly the same charge, viz. $3{\cdot}4 \times 10^{-10}$ electrostatic units (p. 701).

The charge of a corpuscle is not capable of division by any means at present known; it is, as it were, an 'atom of electricity,' and for this reason the corpuscle has also been called an *electron.* An electron is the smallest fragment or detached portion of matter yet known to science.

The β-rays emitted by radium have now been proved to be identical in nature with cathode rays, the main difference being that β-rays have nearly the velocity of light, but the cathode rays only about one-twelfth that velocity.

Ions.—When discussing the laws of electrolysis (p. 740) we explained that in a conducting liquid the electricity is actually *carried* through the liquid by material atoms, or groups of atoms

moving through it; that each atom carries a definite amount of electricity, and that it, with its charge, is called a Kation or an Anion according as it carries positive or negative electricity.

It has also been shown that the only way in which electricity can travel through a gas, or through a so-called vacuum, is by being *carried* through it by rapidly moving particles of matter; these particles, whether they carry positive or whether they carry negative charges, are called *Ions*.

The ions found in gases at ordinary pressures have an apparent size which is large compared with the molecules of the gas in which they are produced.

A *Negative Ion* probably consists of an electron with a cluster of molecules attached to and moving with it.

A *Positive Ion* probably consists of a molecule from which an electron has been expelled, together with a cluster of molecules attached.

At low pressures the negative ion is simply a single electron; *i.e.*, as stated above, it is a fragment of an atom in mass about one-thousandth of the hydrogen atom and carries a definite charge of negative electricity.

The positive ion consists of the remaining piece (nine hundred and ninety-nine thousandths) of an atom from which an electron has been expelled; therefore even at the lowest pressures the positive ion remains of atomic size.

Ionization.—Since electricity can only be carried through a gas by means of ions, it follows that when a charged body, such as a gold leaf electroscope, is surrounded by air or any gas, it cannot be discharged — provided the insulation of its support be perfect—unless ions are present, and the discharge cannot continue unless the supply of ions be maintained. Delicate experiments by Cooke, Rutherford, C. T. R. Wilson, and others, have shown that a slow discharge always takes place, and that its rate corresponds to the production of from 10 to 60 ions per c.c. per second. Such production of ions may be called 'natural ionization' of the gas.

One of the most extraordinary properties of radio-active substances is their ionizing power; thus a gramme of uranium

or thorium will produce many thousand ions per second, and a gramme of radium nearly a billion ions per second.

Röntgen Rays owe their power of discharging an electroscope, on whose leaves they are allowed to fall, to the immense number of ions which they produce.

It may cause surprise that particles so minute as electrons can be counted or indeed dealt with in any manner; we will briefly allude to two experiments which give an idea of the methods employed.

Mr. C. T. R. Wilson, knowing that an ion will serve instead of a dust particle as nucleus for a globule of water in the formation of fog, used the method (p. 343) devised by Mr. Aitken for counting the number of dust particles in air. Air free from dust but containing moisture is placed in a closed vessel, and then made to expand suddenly; this causes a fall of temperature, and moisture condenses into a globule round each ion. The globules can be counted as follows: the size and weight of each can be calculated from measuring the rate at which the fog settles down—the smaller the globules, the slower they fall; the whole fog can then be weighed, and its weight divided by that of a globule gives the number of globules and therefore of ions present.

Professor J. J. Thomson, in working on the deflection of cathode rays by a magnet, placed in a vacuum tube (Fig. 127, p. 808) two metal screens with small circular apertures in line with the cathode; the stream of ions from the cathode was thus cut off, except for a small sheaf or pencil of rays which, passing through the apertures, fell on a fluorescent screen, forming there a disc of light. The pencil of rays, after passing the screens, was subjected to a magnetic force or an electric force of known strength; this caused the stream of ions to deviate, and the deviation being measured enabled various calculations to be made. For example, in many cases it was found that the circular spot was drawn out into an elongated band, and from this it was proved that the ions did not all move with the same velocity.

Nature of X-Rays.—We have seen that X-rays are not

produced directly at the cathode of a tube, but at the surface of any solid upon which the cathode rays impinge. Now the cathode rays consist mainly of negative ions, simple electrons, projected with great velocity; in their rapid movement the electrons produce electro-magnetic effects similar to those of a current of electricity; when suddenly stopped they give effects similar to those (pp. 763, 772) produced by the sudden stoppage of an electric current. Hence, as a surface is bombarded by the electrons, electro-magnetic impulses are given out in an irregular manner from the points of impact. Although each impulse spreads out spherically, the effect due to the series of impulses, on account of their irregularity, differs from a wave of light. Sir George Stokes proved that such rays would not be refracted in change of medium, and would not be deflected by a magnet.

Recent modifications of the atomic theory of Dalton offer an explanation of radio-activity. There is evidence that the atom is a complex whole, built up of many individual sub-atoms, of which electrons are examples, and that these sub-atoms are in a state of extremely rapid motion within the atom. "The data at present available indicate that the number of corpuscles in the atom is equal to the atomic weight."—J. J. THOMSON.

Further, there is evidence that in elements of high atomic weight (*i.e.* those whose atoms are relatively heavy and presumably built up of a greater number of sub-atoms) the atoms are liable to disintegration, a very minute fraction of the entire number of atoms being broken up in the course of a second or even of a year. In the case of radium (a.w. about 224) this minute fraction is much greater than for other elements, and helium (a.w. about 4) is formed as one of the products of the broken-down atoms.

When an atom of radium is broken down, an electron, which was moving at high velocity within the atom, is thrown off from it with that high velocity; the β-rays from radium consist of the (negative) electrons thrown off by the atoms; the α-rays consist of the atoms which have thrown off electrons, and which, therefore, are themselves positive ions. The γ-rays are caused by the electro-magnetic shock given to the ether as each atom is broken down.

CHAPTER IX

TELEGRAPH AND TELEPHONE

Early History—Apparatus Needed—Battery—Line Wires—Receiver—Morse Alphabet—Sender—Telegraph Circuit—Earth Return—Submarine Telegraphs—Multiple Telegraphy—Relays—Telephones—Bell's Telephone—Hughes' Microphone—Wireless Telegraphy.

Early History.—As soon as it was discovered, more than a century ago, that electricity could be made to travel along a wire or a damp string, which had been carefully suspended from insulating supports, the fluttering of the gold leaves of the electroscope and the movements of electrified pith balls at once suggested the idea of giving signals at a distance by means of electricity.

In 1747, at Shooters Hill, near London, Bishop Watson sent the shock from a Leyden jar through two miles of wire hung from wooden poles, but this was a rather violent method of signalling: in 1774 Lesage, at Geneva, arranged twenty-four long wires side by side, and connected each to an electroscope at the far end; each electroscope indicated a letter, hence by charging the wires in proper order words could be spelled out. Owing to the uncertainty of all work with frictional electricity, especially before the days of the Wimshurst machine, these attempts at telegraphy were of no practical use.

The discovery of the voltaic battery put the matter on a different footing; in 1811 Sömmering of Munich constructed a workable telegraph, but it was not till 1837 that the telegraph was made capable of commercial use, a result chiefly due to

Steinheil (Munich), Morse (America), and Wheatstone and Cooke (England).

Apparatus Needed.—The principal things necessary to the working of the telegraph are—

(1) A Battery at each end to provide the current.
(2) Wires to carry the current.
(3) A Receiver (Indicator) to receive the signals.
(4) A Transmitter (Key, Sender) to send the signals.

(1) **Battery.**—The battery can be made up of Leclanché cells if the line be little used; Daniells [Post-Office form] or bichromates, if the line be a busy one. The number of cells in the battery varies according to the length of the line and the diameter of the wire, thus for a line 16 miles long about 20 cells would be used; for 150 miles 80 to 100 cells; for an Atlantic cable only 5 to 10 cells are used, the great delicacy of the receiving apparatus being able to compensate for the very low battery power, which has to be employed on a long cable.

(2) **Line Wires.**—For many years iron wires were used, for although copper conducts six times better than iron it is about twenty times more expensive, hence a bigger iron wire could be used to compensate for its high resistance. However, there is a further objection to iron; on account of its being magnetic, it does not permit working at very great speed. Hence, in late years, on all important lines, the iron wires have been replaced by copper. The wires are suspended from the familiar telegraph poles, and, in order to prevent the current from leaking away through the poles [for even dry wood will conduct a little], they are fastened to earthenware insulators. One of the thousand different forms of insulators is shown in Fig. 129, the object of giving it the umbrella

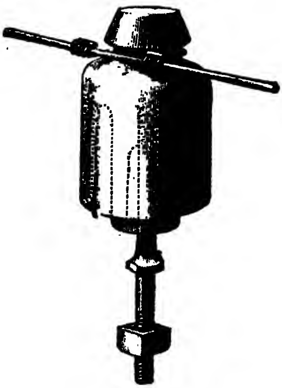


Fig. 129.—Telegraph insulators

bell shape, as dotted in the figure, is that the underside may keep dry in rainy weather, and prevent leakage to the central bolt.

(3) **Receiving Instrument.**—The simplest form of Receiver to describe is the Morse Sounder. It consists of a horse-shoe electro-magnet MM, whose soft iron 'armature' A (not to be confused with the 'armature' of a dynamo) is fixed at the end of a lever LL. When no current passes, the end of the lever is held by the spring S against the stop T. But as soon as a current passes through the electro-magnet the armature is attracted, and the lever strikes with a sharp click against the upper stop U; a second click of a different tone is heard as the lever strikes the lower stop when the current ceases. If the current pass for a

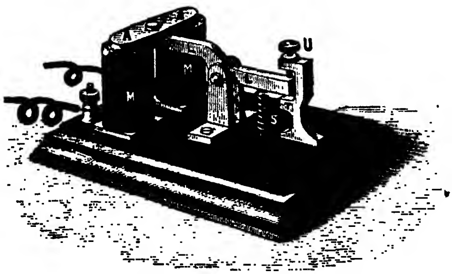


Fig. 130.—Morse sounder.

short time only, the two clicks come close together, and the signal is known as a 'short' or a 'dot' (-) If the current pass for a longer time the clicks are separated by a longer interval, and the signal is called a 'long' or a 'dash' (—).

Morse Alphabet.—In the year 1837, Alfred Vail, of Speedwell, the partner of Professor Morse, compiled an alphabet "based on the elements of time and space," or as we should call it, "dot and dash," and he also designed the instrument described as the "Morse Writer." These have always been known by the name of Morse, because he was the surviving partner. The original alphabet is used in the Americas and Canada; in Europe and the countries to the east of it, which are signatories to the International Telegraph Convention, a modification is used.

Letter.	Morse Signal. International.	Morse Signal. American.	Letter.	Morse Signal. International.	Morse Signal. American.
A	· —	· —	K	— · —	— · —
E	·	·	L	· — · ·	——
I	· ·	· ·	M	— —	— —
O	— — —	· · *	N	— ·	— ·
U	· · —	· · —	P	· — — ·	· · · · ·
Y	— · — —	· · · · *	Q	— — · —	· · —
			R	· — ·	· · · *
B	— · · ·	— · · ·	S	· · ·	· · ·
C	— · — ·	· · · *	T	—	—
D	— · ·	— · ·	V	· · · —	· · · —
F	· · — ·	· — ·	W	· — —	· — —
G	— — ·	— — ·	X	— · · —	· — · ·
H	· · · ·	· · · ·	Z	— — · ·	· · · · *
J	· — — —	— · — ·		* These are called	spaced letters.

The Morse dot and dash are used for signalling by sounder, flashing-lamp, 'flag-wagging,' disc and heliograph; in needle instrument and siphon recorder, left and right, or up and down, correspond to dot and dash.

In the Morse 'Writer' the electrical arrangement is the same as in the 'Sounder'; but the end of the lever is fitted with a style, or point, close above which there is fitted a small cylinder smeared with a specially prepared ink, and made to turn slowly. A long strip of paper from a roll passes between the style and the inky cylinder, and is drawn along by clockwork. Whenever the current passes the style presses the paper against the cylinder. A short current makes a dot on the paper, and a longer one makes a line or 'dash.' We give a specimen—

Fig. 131.—Specimen message by Morse writer.

(4) **Sending Instrument.**—The Sender is simply a key for starting and stopping the current. The figure (Fig. 132) needs little explanation. A is connected to the line, B to our receiving instrument, C to our battery. When the key is untouched any current arriving from the line can pass *viâ* A and B to our receiver. When the key is depressed the connection at B is broken,

so that no current can pass to our receiver, but the current from our battery passes *viâ* C and A to the line, and thence to the distant receiver.

Telegraph Circuit.—The arrangement of the wires and instruments for sending from one place to another, say Bristol to

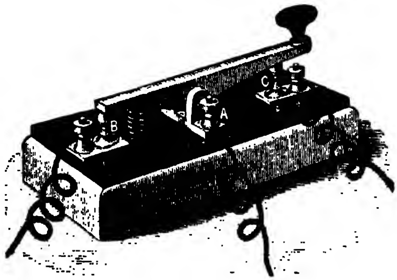


Fig. 132.—Morse sending key.

Exeter, is shown in Fig. 133; as represented, no current flows through the Exeter battery, because its circuit is broken, the wire from its copper stops short at the terminal C. But at Bristol the key is depressed, the current from the Bristol battery is,

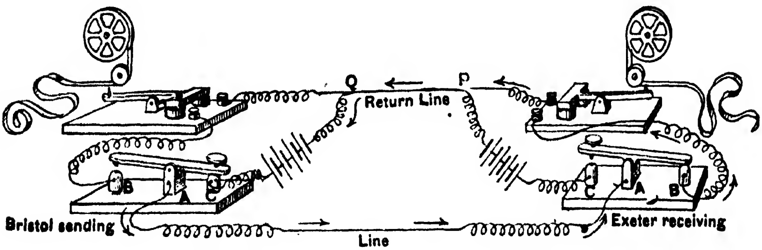


Fig. 133.—Connections of instruments for two stations.

therefore, able to make its way from C to A into the line; arriving at Exeter it passes through the key from A to B, through the receiver, and back to Bristol by the return wire. Arriving at Bristol, the path through the receiver is blocked at B, hence the only course open for the current is to return to the battery, thus completing its circuit.

Earth Return.—As a matter of fact *no return wire* is used, for as early as 1837 Steinheil made the important discovery that the current could make its return journey through the earth. All that is necessary is to bury a big sheet of iron or any metal in a damp place close to the telegraph office at Exeter, and a similar one at Bristol. Wires from P and Q are connected to these plates. The current is thus able to escape from the wire into the earth at one end, and to climb out of the earth back to the battery at the other.

Beginners are often puzzled with the thoughts, 'How does the current *find its way back?*' and 'How is it the currents from different places don't get mixed?' Perhaps the most honest way of answering is that the electricity does *not* find its way back, and that the different currents do get mixed. Certainly at the receiving office electricity—whatever it is—pours out of

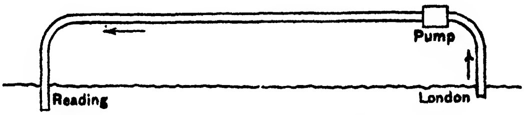


Fig. 134.—Explanation of earth return.

the instrument into the earth, and at the sending station electricity comes up out of the earth into the battery, but it is not necessarily the same electricity.

We may illustrate this by a water analogy. Suppose a long pipe to lead from London to Reading, let its two ends dip into the Thames, let it be filled with water, and provided with a force pump in London. The pipe thus corresponds to the conducting wire, its open ends to the two earth plates, the pump corresponds to the battery, and the Thames to the earth. If now the pump be worked, and force gallon after gallon of water out of the pipe at Reading, obviously it must suck up gallon after gallon at London, but these gallons sucked up almost certainly are not the same gallons that have been poured out at Reading. Then does not the water flow back at all from Reading to London? Of course *some* water does. The effect of the outpour at Reading

is to raise the level imperceptibly there, and the effect of the intaking in London is to lower the level there. The difference of level thus produced will in so large a river cause a very sluggish and quite imperceptible stream to flow, yet the flow will take place.

So with our Bristol-Exeter telegraph, the outpour of electricity at Exeter will raise the electric potential (*i.e.* electric level) of the earth round about Exeter, and the intake of electricity (or outpour of – electricity) at Bristol will lower the potential of the earth near the Bristol office. The difference of potential will therefore cause an imperceptible current to flow back through the earth from Exeter to Bristol.

Notice that if we had a return pipe from Reading to London, and the stream of water had to be forced back through it instead of flowing along the open river, the pump would have more work to do. So with electricity, when we have a return wire the battery has more work to do to force the current through it than when the current flows through the 'wide, wide world.' Hence the abolition of the return wire not only saves the expense of erecting one, but is a positive advantage to the working of the telegraph.

Submarine Telegraphs.—These do not in principle differ from the telegraph just described, though there are many difficulties to be overcome in their use. The first difficulty is to provide a 'line' strong enough to stand the rough wear of rocks in shallow water and the strain of lowering to the bed of the ocean, and at the same time perfectly insulated. In the Atlantic cables there is a central 'conductor' of seven copper wires twisted together. This is surrounded with guttapercha, then with hemp, which has been served with tar, oil, and beeswax, and outside of all is a protecting cover of steel wires wound spirally.

The second difficulty is that the cable behaves like a gigantic Leyden jar; the copper wires form its inner coat, the gutta-percha, etc., correspond to the glass of the jar, and the steel covering and water to the outer coat. Hence a battery of low

E.M.F. must be used, otherwise a dangerously large charge would be given to the cable. When a battery is connected to the copper conductor at one end it has to charge up all the near part of the cable before the current makes its way to the distant end; in fact, in the Atlantic cables it takes about one-fifth of a second before any trace of a current reaches the other side. The current flows in much the same way as the tide does in some rivers—first, a big wave that travels somewhat slowly along; in front of it no tide, behind it a rapid stream. Three thousand miles in one-fifth of a second can hardly be called slow, yet it is too slow for the economical sending of messages, and special methods of counteracting this trouble had to be devised. We have not room to describe them.

The third difficulty is that the current, which can be forced by a small E.M.F. through a long cable having a high resistance, is very weak, and would be quite incapable of working the ordinary Morse Sounder or the Needle instrument. At first the current was received in a Reflecting Galvanometer; in fact, Lord Kelvin (Sir William Thomson) invented this galvanometer for the purpose, and the message was read by watching the movements of the spot of light to the right or left. At present Lord Kelvin's 'Siphon-recorder' is universally used for long submarine cables. In this the current passes through a very light coil of fine copper wire, suspended by a silk thread between the poles of a set of horse-shoe magnets. The coil carries a light glass siphon with a long arm or pointer, from the end of which a fine jet of ink is spurted out and made to trace a line on a paper strip, which is drawn along close to the pointer. The coil moves so easily that the slightest current is able to affect it, and each movement is recorded as a wave in the inky line.

Multiple Telegraphy.—The utility of the telegraph on busy lines has been increased greatly by various methods invented for sending more than one message along the same wire at the same time. We can only give without details a hint as to the way in which this is done.

DUPLEX SYSTEM (for sending one message from each office).

—The arrangement of wires, batteries, and instruments is given in the diagram, a possible distribution of resistances being given. The coiled lines represent resistance coils purposely inserted. The resistance of the 'line' is taken as 1000 ohms, while the resistances of the earth, the batteries, and of short connecting wires is neglected.

Suppose the London key K depressed, a current flows from the battery and splits at O into two branches; the first branch flows *viâ* A and C to the earth and back to the battery; the second branch flows along OL, then follows the line to L′; at L′ it again splits, about half of it ($\frac{1}{4}$ original current) flowing from L′

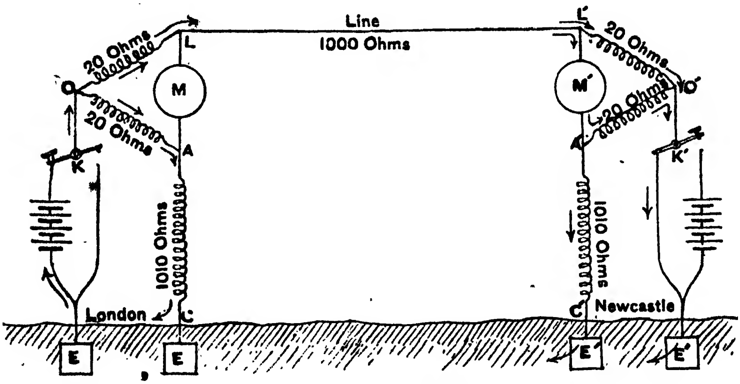


Fig. 135.—Multiple telegraphy.

to O′ and thence *viâ* K′ to the earth. The other half ($\frac{1}{4}$ original current) flows through the Morse receiving instrument M′, where it makes a signal, it then goes on to A′, where a trifling fraction flows through the high resistance 1010 ohms to C′ and the earth, but the greater part flows through the 20 ohms to O′, and thence through the key K′ to the earth.

Thus, depressing the London key gives a signal at Newcastle. But will it also affect the London instrument M? No! We will try to show why not.

The path of the current from L′ to the earth plates E′, by having two or three routes to branch along is rendered more

easy than if only the 20-ohm path L′O′ were open; hence the 'effective resistance' to the current from L′ to the earth is about 10 ohms, which, added to the resistance of the line, gives about 1010 ohms as the resistance from L to the earth at E′. Hence, again tracing the current from its first split at O, along one path there is resistance 20 ohms O to L, followed by 1010 ohms L to E′; along the other path 20 ohms O to A, followed by 1010 ohms A to E: hence L and A are in just the same electrical position, they are at the same potential, and there is no E.M.F. to drive the current from L to A through the instrument M. Similarly, Newcastle can send a signal to London without disturbing its own receiving instrument M′.

If both want to send a signal at the same time, both keys K and K′ are depressed; each battery struggles with equal E.M.F. to send a current in opposite directions along the line, there is a deadlock, and no current whatever passes in the line; yet each receiving instrument, acted on by its own battery, gives a signal which is as useful as if it came from the distant place.

This is called the 'bridge' method because, as in the Wheatstone bridge, the circuits are balanced so that no current passes through the sender's receiving instrument.

Land lines are now usually duplexed on the 'differential' method. Each receiving instrument is wound with two coils; the operator sends through one of these coils his line current and through the other a local current of equal strength and opposite direction; these neutralise each other and leave the instrument to be actuated by the distant station.

Relays.—The line currents are not usually strong enough to work the receiving instruments, and a *relay* is used. This is an electro-magnet with a light armature kept away from a contact pin by a spring; the line current causes the electro-magnet to attract the armature and make contact, bringing a local battery into circuit with the receiving instruments. A long line is usually divided into sections, from each of which the message is automatically transmitted to the next by a relay.

For information concerning polarised relays and double

current working, the various printing and other receiving instruments, as well as the refinements of line insulation and balancing, refer to *Telegraphy and Telephony*, Crotch (Spon), or *Telegraphy*, Herbert (Whittaker).

Telephones.—Telephones are instruments for conveying sound to a distance; as early as 1860 an instrument was designed by Reis which was capable of conveying musical sounds, which consist in comparatively simple vibrations, but it was incapable of properly transmitting the complicated vibrations of human speech. In all telephones there are two essential parts—(1) an instrument to be spoken into called the Transmitter; (2) an instrument to be listened to at the distant

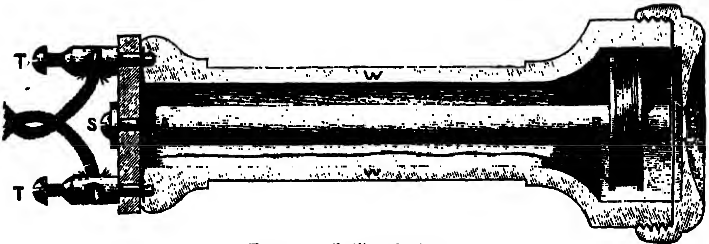


Fig. 136.—Bell's telephone.

place called the Receiver. The Receiver devised by Reis was fairly perfect, but the Transmitter was inefficient, and it was not till Graham Bell in 1876 invented his instrument that the telephone became of practical use for speaking. Bell's Receiver was identically the same as his Transmitter, and still, with various trivial modifications, continues to be the type of all Receivers; it has dropped out of use as a Transmitter owing to adoption of the Microphone Transmitter, invented by Hughes in 1878.

Bell's Telephone (used as a Receiver).—A long magnet AB is fixed in a wooden or ebonite block WW, of the well-known shape shown in Fig. 136. Round the pole B of the magnet is fixed a coil C of fine insulated wire, whose ends are connected with the terminals T, T. A plate P of very thin sheet-iron (usually called ferrotype iron, and similar to that used by cheap

likeness-while-you-wait photographers) is held firmly at the edge (by a cap or ring which is screwed over it), so that the centre of the plate is very close to the pole B of the magnet.

If a battery be connected to T, T, the current thus made to pass round the coil C increases the strength of the magnet AB, and gives an extra pull at the centre of the disc P, causing it to bulge inwards, just as the lid of a tin box does when any one sits on it; if now from any cause the current be slightly increased, the disc is attracted more powerfully and its inward bulge is increased, and if, on the other hand, the current be decreased slightly the disc springs back a little. The disc is extremely sensitive to the fluctuations of the current; hence it is able to follow and to vibrate exactly in time with the sound-vibrations which (as explained in the next paragraph) produce fluctuations of current in the Transmitter at the distant station whenever it is spoken into. Since sound consists merely of vibrations, the disc in vibrating gives out an exact copy of the spoken sound, and it is this copy which we hear when we apply the ear to the opening in front of the disc P.

Hughes' Microphone.—The microphone consists essentially of a rod of carbon with sharpened ends which rest loosely in cups hollowed out in two blocks of carbon. These blocks are connected to terminals from which wires lead to a battery of a few cells, in whose circuit a telephone is also placed. In the improved microphone, whose interior is shown in Fig. 137, there are six short carbon rods C, C, which lie each with one end resting lightly in a cavity in the central carbon block. The other ends of the rods rest each in one of the small outer carbon blocks, which are themselves firmly screwed to the two forked strips of copper on the base board. A current arriving by one of the terminals BB passes to a copper strip, thence splitting into three branches it follows three of the rods CC to the central block, and thence it again flows in three branches along the remaining rods to the further copper strip, and finally passes out through the other terminal to the outside circuit. The working of the instrument depends on the fact of there being considerable

electrical resistance to the passage of the current at the point where a rod lies loosely against its support; an increase of pressure at the point of contact allows the current to pass more easily, while a decrease of pressure increases the resistance; hence when any sound produced near the instrument causes the rods and their supports to vibrate, the variations of resistance caused by the varying pressure at the loose contacts cause in the current vibrations which keep exact time with those of the sound: the fluctuating current passes through the telephone and there reproduces, as explained in the last paragraph, a copy of the sound which agitates the microphone.

It is to be noted that it is the electric current, deriving its

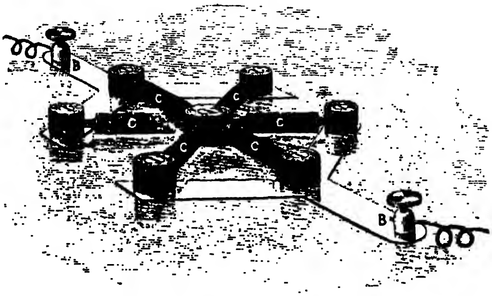


Fig. 137.—Microphone transmitter.

energy from the battery, which does the sound-producing work in the telephone: the sound near the microphone merely opens and shuts as it were a tap for the passage of the current, and just as a child can open the valve for a powerful steam syren, so a very feeble sound may suffice to start and stop the current, and thus produce a fairly loud sound in a distant telephone.

The microphone is so sensitive as to transmit the sound produced by the tramp of a fly across its sounding board. Hence its name, from μικρὰ, *micra*, small, and φωνὴ, *phōné*, a sound.

Before the invention of the microphone, Bell's telephone had to be used for transmitting as well as receiving: in this case no

battery is used, but the vibrations caused by the voice in the iron plate P, bringing it nearer to or further from the pole of the magnet and its coil C, cause variations in the induced magnetism, and these again cause induced electric currents in the coils; the induced currents travel along the wires to the distant telephone, and there reproduce the original sound.

The telephone familiar to us in a modern exchange is a 'watch' receiver and a 'solid-back' transmitter combined. A 'watch' receiver is a Bell telephone; the magnet is a ring placed parallel to the ferrotype plate, with two pole-pieces wound with coils of wire brought close to the plate. The transmitter is a box filled with carbon granules; the back or bottom of the box is a brass plate faced with carbon; a similar plate is fastened at its centre to the mica top of the box and to a ferrotype plate, clamped at its edge and vibrating with the voice. The current passes between the two brass plates, and the granules act as a microphone.

Wireless Telegraphy. I. PREECE.—Telegraphy without the use of a line wire has been known in one form or another for many years. In 1859 Lindsay sent signals across the Tay where it was three-quarters of a mile wide. In 1882 Sir W. Preece sent messages across the Solent from Portsmouth to the Isle of Wight. In 1886, when the cable to the Scilly Isles was broken down, messages which were passing in the neighbouring French Atlantic cable were read on the broken-down Scilly cable: and in 1892 Sir W. Preece sent messages from the coast of S. Wales to the Flatholm, an island 3 miles distant in the Bristol Channel. His signalling depended on electromagnetic induction—it was in fact merely the carrying out on a large scale of the experiment described, pp. 761, 762. Two loops of wire [1] were erected roughly parallel to each other, one nearly a mile long on the mainland, one 600 yards long on the island. Rapidly repeated starting and stopping of the current in one loop (corresponding to coil A) caused kicks of current in the other loop (corresponding to coil

[1] The loops were not actually complete, an 'earth return' being used in each. This fact makes it possible that the sound in the telephone may have been partly caused by the primary current spreading out across the channel.

B); these kicks caused a buzzing noise in a telephone connected to this loop. Combinations of 'short' buzzes and 'long' buzzes gave the message in the Morse alphabet.

II. Hertz, Lodge, Marconi.—Whenever a spark passes between two knobs connected with a Ruhmkorff coil or a Leyden jar, a violent rush of electricity occurs which may be accompanied by an oscillation or surging of electricity in any conductors connected with them.

Just as the explosion of a mine under the sea will send out a set of waves expanding in ever-widening circles over the surface, so this surging gives rise to an electric disturbance which spreads in widening spheres throughout space. The existence of such a disturbance was proved experimentally in 1887 by Hertz, whose early death in 1894 was a great loss to science.

The waves from the explosion will, when they reach a distant boat, set it rolling; and the rolling will be most violent when the 'period' (p. 423) of the waves happens to be the same as the period of swing of the boat. So when the radiating electric disturbance reaches any distant conductor it causes electricity to surge about in that conductor. Hertz arranged a conductor so that the natural time of swing of electricity within it agreed with that due to the exciting sparks, and then found that the secondary surgings in this distant conductor gave rise to sparks whenever sparking occurred at the coil or jar. This effect was produced at distances up to about twenty yards.

In 1889-90 Branly and Prof. Oliver Lodge arranged delicate detectors (called 'coherers') of the Hertz waves. It was found that a glass tube packed loosely with iron or copper filings, when placed in the circuit of an ordinary battery, offered so much resistance that scarcely any current was indicated by a galvanometer included in the circuit; but when a spark was produced in a coil distant over fifty yards, the filings in the tube immediately began to conduct readily and would continue to conduct until disturbed by tapping or shaking.

The cause appears to be that, whenever two filings are rest-

ing together in light contact, high electric resistance occurs; a distant spark causes surging in the particles, and, in consequence, minute sparks—far too minute to be visible—pass between them. This causes a delicate welding of the particles together, a welding sufficient to materially lower the resistance, yet so slight as to be fractured by a very feeble mechanical jar.

The Italian physicist Marconi has seized on this discovery, and, having experimented as to the most sensitive material to be placed in the tube, has constructed an ingenious apparatus which will respond to the Hertz disturbances even at thousands of miles' distance (it should be noted that they are then many million times more feeble than at fifty yards). The details of his apparatus need not be described: the main features are as follows—a weak current through the coherer actuates a 'Relay'; the current through the relay gives the signal and also works a tiny hammer, which taps upon the coherer, thus restoring its high resistance, stopping the current in it, and leaving it sensitive and ready to receive the next surging signal which arrives.

The most sensitive method of receiving messages is to put a telephone in circuit with the coherer: it is by this method that the most distant messages have been received.

Wireless Telephony is effected by superposing the complex changes of current, due to the motion of the microphone diaphragm, on a high-frequency aerial discharge. Only by using high frequency is it possible to affect a distant receiver, while using a comparatively small quantity of electricity, and to transmit the higher harmonics, which give the sounds of speech their character. Duddell's "singing arc" controlled by a magnetic field has been used by Poulsen, as it gives a series of rapidly intermittent electrical rushes, or the current may be developed by a high-frequency alternator. The form of the sound-waves is imposed on these vibrations by employing a microphone directly in the aerial wire in series with the alternator or in series with the current inducing the magnetic field.

CHAPTER X

Dynamos and Motors

Dynamos—Faraday's Disc, as a Dynamo, as a Motor—Magneto Machine—Collector and Commutator—Gramme Machine—Field Winding—Series—Shunt—Compound—Modern Generators—Armature Winding—Armature Reaction—D.C. Motors—Commutation—Efficiency—Alternators—Polyphase Working—Polyphase Motors—Rotary Converters—Single Phase Series Motor.

Dynamos. — Dynamos are machines for producing electric currents by means of mechanical work: the word dynamo is derived from the same word as dynamics (Greek δύναμις, *dynamis*, force or power), for in the dynamo the force of a man, a steam-engine, or a water-wheel is utilised to drive the machine, and so to convert mechanical energy into electrical energy.

The working of all dynamos depends on the principles of magneto-electric induction, which we discussed in Chap. VI.; in all of them either a magnet is moved in the neighbourhood of a coil, or a coil is moved in the neighbourhood of a magnet, and the magnet used may be either a permanent magnet or an electro-magnet. In the earliest dynamos (then called magneto-electric machines) permanent magnets were used, but at the present time their place is taken by electro-magnets, which are so much more powerful; in the case of the small dynamos used for medical coils, for magneto-ignition in motors, or for working call-bells for telephones permanent magnets are often retained.

After explaining Faraday's disc, we will describe machines of each type, taking first the magneto-electric machine, and then the Gramme and the Siemens dynamos.

Faraday's Disc.—This interesting piece of apparatus is

represented in Fig. 138: it consists of a copper disc mounted lightly on a spindle, so that it can rotate between the poles of a vertical horse-shoe magnet; the bearings of the spindle are insulated from the magnet, but have a connecting wire leading down the magnet and under the base board to one of the binding screws; the rim of the disc is well amalgamated with

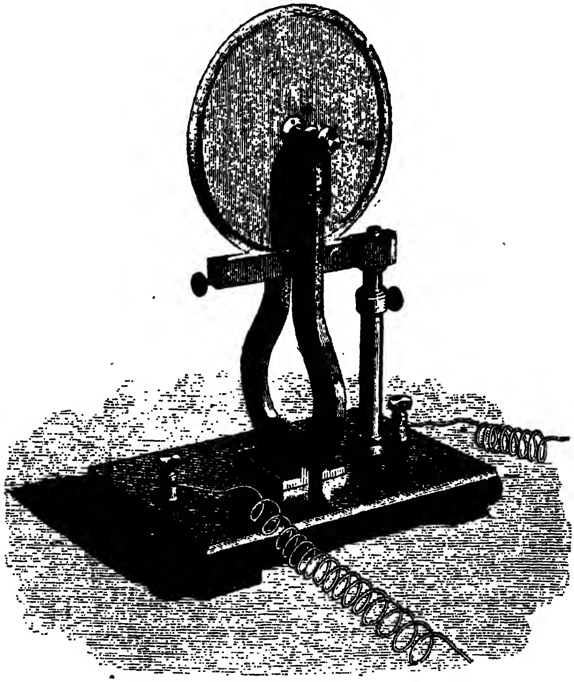


Fig. 138.—Faraday's disc.

mercury and dips at its lowest point into a narrow trough of mercury from which there is a connection by way of the upright column to the other binding screw. Wires from the binding screws can be led either to a battery or to a galvanometer as desired. The disc can be spun by means of a small pulley on the spindle.

The Disc as a Dynamo.—Faraday's disc was invented by him in 1831, and is of peculiar interest from the fact of its being the first machine in which a continuous current of electricity was produced by the help of magnetism and motion. It was therefore the forerunner of all dynamos and magneto-electric machines. It was designed in the course of those classic researches of the great Faraday in which he brought to light the fact that currents of electricity could be produced by magnetic action. The instrument is of further interest, because its action—although difficult to understand by means of the laws of induction as we gave them in Chap. VI.—illustrates simply another way in which the laws may be expressed.

LAW OF INDUCTION. — "Whenever a wire, or other conductor, moves so as to cut through lines of magnetic force, an E.M.F. is set up in it equal to the number of lines of force cut through per second."

Now the Faraday disc is traversed at right angles by the lines of force running from the N pole to the S pole of the magnet: hence when the disc is rotated the vertical radius from the mercury trough to the spindle is always cutting perpendicularly through the lines of force. By connecting the binding screws to a galvanometer we may verify the fact discovered by Faraday that a current flows continuously from spindle to trough or *vice versâ* so long as the spinning is continued; and that the direction of the current is reversed when the direction of spinning is reversed.

The direction of the current may be ascertained by the help of Fleming's rule, which is as follows :—

FLEMING'S RULE, Part I. (Current induced by motion).—Having clenched the *right hand*, open out the thumb and two fingers as in Fig. 55, then place the hand so that the index finger points along the lines of force, and the thumb points in the direction of motion, then the induced current flows in the direction in which the mid finger points.

Applying this rule to the disc, as shown in Fig. 138; if the disc be spinning 'clockwise' and the N pole of magnet towards

us, then the forefinger must point from us through the paper; the thumb points to the left, hence the mid finger shows that the current flows downward from spindle to trough. While if the rotation be 'anti-clockwise' we see, by twisting the hand at the wrist until the thumb points to the right, that the current then flows upwards.

The Disc as a Motor.—If the wires from the binding screws be led to a battery we find that whenever the circuit is completed the disc is set in rotation by the passage of the current along its vertical radius: a reversal of the battery current causes a reversal of the direction of rotation.

Attention to Lenz's Law (p. 763) at once gives us the direction of rotation: when the disc is used as a dynamo the induced current flows in such a direction as to oppose the force which produces the motion; hence conversely when we supply the disc with a current the direction of motion is opposite to that which would produce the current. That is in Fig. 138, if the current flow upward from trough to spindle, the rotation is 'clockwise' and *vice versâ*.

If we open out the thumb and two fingers of both right hand and left hand a glance shows that the thumbs point in opposite directions; this fact at once leads us to the following:—

FLEMING'S RULE, Part II. (Motion induced by current).—Place the *left hand* in a position similar to that of the right hand in Part I., then the thumb points in the direction of motion.

Magneto Machine.—The 'magneto-electric' machine was invented by Pixii in 1833 and subsequently improved by Clarke and others. The form we describe is a lecture apparatus designed to show the parts clearly.

A powerful horse-shoe magnet NS, generally built up of two or three separate magnets bolted together, is fixed on a wooden frame, shown in the figure. C and D are coils at each end of a soft iron bar, which is mounted on the spindle P so that it can be spun rapidly by means of the handle and driving gear. The same wire is wound in succession round both coils,

but care must be taken, as in winding an electro-magnet, to wind C in the opposite way to D. The coils are wound on soft iron cores, so that the revolving bar with its pair of coils is practically an electro-magnet, the difference being that, instead of supplying it with a current so as to produce magnetism, we supply it with magnetism so as to produce a current. When the coils are in the position shown in Fig. 139 their soft iron cores and connecting bar are strongly magnetised by the induction of the permanent magnet; C has a S pole facing the N pole of the permanent

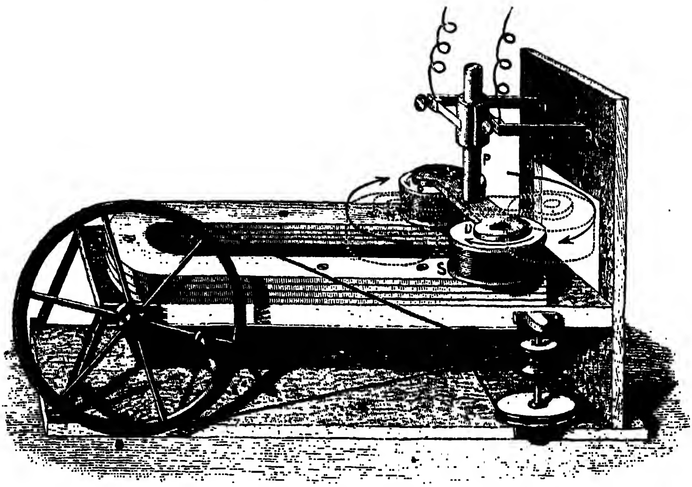


Fig. 139.—Magneto-machine—Position I.

magnet, and D has a N pole facing the S pole of the permanent magnet, so that many lines of force pass through the coils in the direction NCDS.

After the spindle has been twisted through a quarter turn the coils are in the symmetrical position shown in Fig. 140, and the cores are no longer magnetised, for each is equi-distant from the N and S poles of the permanent magnet, and there is, therefore, no reason why one more than the other should have a N pole. In this position no lines of force pass through the

coils, hence in passing from the first to the second position the number of lines of force passing through the coils has been continually diminishing, and a current flowing in the direction of the small arrows is induced in the coils (as in Experiment 4, described on p. 765).

During the next quarter-turn the coils approach position III., the cores become again magnetised, but the lines of force are threaded through them in the opposite direction, for D is near the N pole of the permanent magnet, so that the lines of force enter the coils through D and emerge at C: the effect of increasing the number of lines threaded in an opposite direction is the same as that of decreasing the number of lines in the original direction, hence during this quarter-turn there is an induced current still in the direction of the small arrows, in Fig. 140.

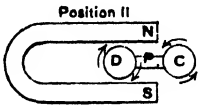


Fig. 140.
Magneto-machine—Position II.

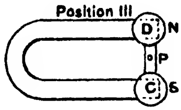


Fig. 141.
Magneto-machine—Position III.

Careful consideration will show that during the next half-turn everything is reversed, the coil D makes the same movement that C made in the first half-turn, hence the current induced in D will flow in the direction of C's small arrows in Figs. 139, 140, that is, the current in it is reversed. Similarly the current in C is reversed.

Collector and Commutator.—The next question is, how to utilise the current generated in the coils during their spin. If we merely wish to get a shock, the direction of the current is immaterial—in fact an alternating current, that is, one first in one direction and then the other, is more effective than a continuous current—the ends of the wire from the coils may be fastened, as in Fig. 142, to two metal rings carefully insulated and mounted on the spindle: two springy strips of brass called brushes are fastened to the binding screws A, B, so as to press

against the rings and thus carry off the current to the wires W, W.

If we wish the current to flow always in the same direction in the wires of the external circuit, we must use a **commutator** (*i.e.* changer) in place of the rings; the ends of the wire from the coils are brought to two half rings, T, U, insulated from each other by two gaps, one of which is shown in Fig. 143. The brushes are fixed on opposite sides of the spindle, so that one is in contact with each of the half rings. During the half-turn, when the current comes out of C, its half-ring T is in contact with A; and during the next half-turn, while the current comes out of D, the spindle is turned the other way, U is in contact with A, and therefore the current still emerges from the machine

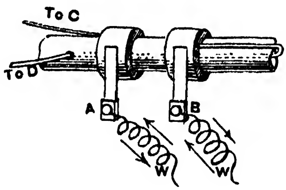


Fig. 142.—Collectors

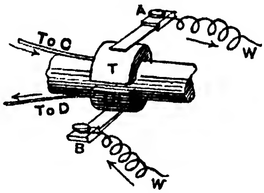


Fig. 143.—Commutator.

by the terminal A and returns to it by the terminal B; hence we call A the positive terminal of the machine and B the negative terminal.

Gramme Machine.—In the course of time various improvements were made in dynamo construction, but no great advance was made until, in 1871, Gramme of Paris invented his 'Gramme Ring': it was his inventions, followed rapidly by those of Siemens, that rendered electric lighting commercially practicable.

To understand Gramme's machine, let us consider what will happen in a small coil or ring of wire which is made to pass in succession through the positions numbered 1 to 8 between the enlarged pole pieces of the magnet shown in Fig. 144. The lines of magnetic force run from N to S almost as straight lines;

at 1 the greatest possible number of lines pass through the coil; moving on past 2 the number of lines is decreased until at 3 no lines pass through the coil. Further movement through 4 to 5 causes the lines again to pass through the coil, *but in the opposite direction*, they now pass from *b* to *a* instead of *a* to *b*, hence the induced current flows round the coil in the same direction for all the positions from 1 to 5; this direction is shown by the small arrows. Continuing the movement through 6, 7, 8, the induced current flows in the opposite direction *along the wire*, although in the figure it seems to be in the same direction, for

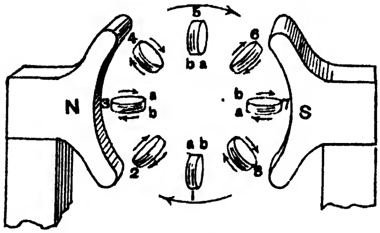


Fig. 144.—Current induced in coil.

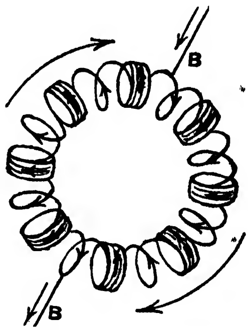


Fig. 145.—Eight coils connected in series.

the coil is turned over; at 1 and at 5, where the change takes place from one direction to the other, no current is induced in the coil.

Now instead of a single coil let us consider eight coils, one in each of the positions 1 to 8, and let these coils be connected together end to end, so as to make one continuous coiled ring of wire: clearly each coil acts in the same way as the single coil in the same position, hence the left-hand half and the right-hand half of the ring tend with equal force to drive a current in opposite directions round the ring, and in consequence no current at all is able to flow.

How then are we to utilise these opposing currents? By the help of a 'commutator' similar to the one we used in the mag-

neto machine: but as we now have eight coils instead of two, we must have eight 'segments' in the commutator instead of the two half-rings before used. The 'segments' are small strips or blocks of copper placed regularly round the spindle, and insulated from one another by air gaps or by strips of mica placed between them. Two brushes press against the commutator, one being in contact with the segment that happens to be highest, and the other with the segment that is lowest, as at BB in Fig. 145. In practice a slight 'lead' has to be given to the brushes; that is instead of being absolutely at the highest and lowest points of the commutator they are shifted forward in the direction of rotation.

A wire is led to each segment from the corresponding junction of two coils in the ring. In this way the currents flowing down the right-hand and left-hand halves of the ring, in lieu of fighting, are enabled to unite at the bottom of the ring, and flowing along the wire to the lowest segment and brush are enabled to pass *viâ* a terminal to the external circuit. Thence they return to the upper brush, the highest segment, and to the top of the ring, where they again split into two parts, each flowing down its own side of the ring.

In the actual Gramme dynamo there are usually about twenty-four coils in the ring, they are wound close together on a soft iron core, which serves the double purpose of holding the coils in position and of concentrating the lines of force of the fixed magnet, so that as many lines as possible may pass through the coils.

If the core were made in one solid piece, the same movement which generates currents in the coils would generate them in the core. These currents—eddy currents (see p. 767)—cannot be utilised, and they possess two disadvantages; first, they tend to heat the core, secondly, they make the work of driving the dynamo more heavy. To avoid this the core is built up of iron wire wound round and round to make a ring, and the wire is covered with an insulating varnish at the time of winding, so as to resist the passage of a current from one turn of the wire to another.

The simple form of Gramme machine has a group of three or four permanent horse-shoe magnets with enlarged pole pieces, such as are shown at N and S in Fig. 144. These magnets are called the *Field Magnets*, because they produce the magnetic field in which the coils spin. The revolving ring with its coils and commutator is called the *Armature*. (*N.B.* The armature of a dynamo must not be confounded with the armature of a magnet, of which we spoke on p. 637.)

It was soon seen that a dynamo giving much more powerful results could be obtained by using electro-magnets instead of permanent magnets for the field magnets; as a rule a current produced in the dynamo itself is used to excite them.

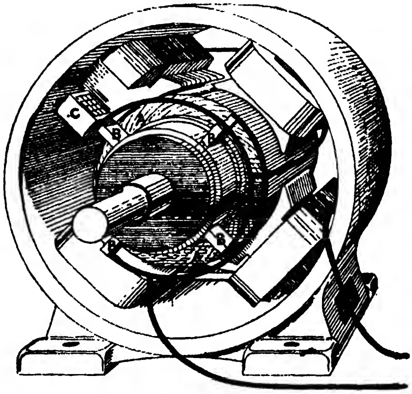


Fig. 146.—Series winding.

Field Winding.—Figs. 146, 147 represent two drum-wound machines (see p. 844, Modern Generators), with the end brackets removed and the armatures A, A and brushes B, B in position.

(1) **Series.**—If the current from the brushes pass, as in Fig. 146, round the field magnets and the external circuit in *series*, the dynamo is said to be 'series wound.' Since in such a dynamo the field magnets are excited by identically the same current as flows in the external circuit, the strength of the field magnets, and therefore also the voltage, rises and falls as the

current in the line rises and falls; that is, the E.M.F. rises as the load rises. This system of winding is not used for main generators, but is used to a large extent for motors and for some auxiliary machines.

(2) **Shunt.**—If the field coils be connected up to the brushes, as in Fig. 147, the dynamo is 'shunt wound.' Since in this case the main voltage of the machine is impressed upon the field, a great length of fine wire is used in the field coils. In each figure a field coil C is given in section showing a large number

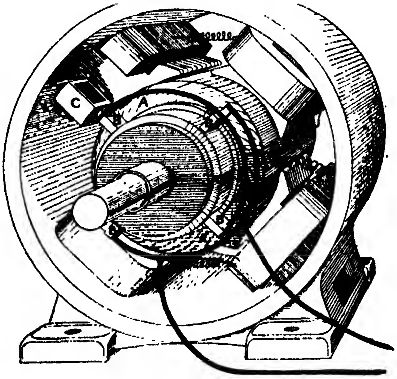


Fig. 147.—Shunt winding.

of turns of fine wire in the case of the shunt machine (Fig. 147) and a few turns of heavy wire in the series machine (Fig. 146).

In a shunt dynamo the greater part of the current from the armature flows round the external circuit, a small quantity being shunted to the field magnets. When the external resistance is lowered, the current in the line increases, and therefore the voltage-drop due to the resistance of the armature increases so that the voltage at the brushes is diminished. For this reason the exciting current is also diminished and there is a still greater drop of voltage as the load increases. Shunt dynamos are mostly used where the load is not subject to any

great and sudden variations. Voltage regulation is obtained by a rheostat in series with the field, the rheostat being adjusted by hand until the voltage reaches the desired value.

(3) **Compound.**—Compound winding is a combination of these methods. The field magnets are wound with two wires—the one, fine, is connected as a shunt; the other, thick, is connected in series, and has sufficient turns to keep up the voltage when the current rises to full load. The generator illustrated in Fig. 148 is compound wound.

It is the object so to proportion the series and shunt coils that the voltage remains practically constant for all loads.

It is well to remember that the load, or power-output, measured in watts, is equal to the number of amperes multiplied by the number of volts; and that 1 k.w. = 1·34 H.P.

It is a common practice nowadays to over-compound, *i.e.* so to increase the series turns that the voltage increases slightly with the load; this is done to allow for the drop of pressure in the line and so to keep up the pressure at the point where the power is used, allowing slight fluctuations near the dynamo.

The self-excited dynamo somewhat reminds us of the mythical 'first hen' which laid the egg from which it was itself hatched, for the current induced in the armature, before going to the external circuit, is made to circulate round the field magnets, 'exciting' them and so enabling them to induce the current in the armature itself. This paradox is easily explained. When the machine is at rest the iron cores of the field magnets retain a feeble trace of magnetism; this induces a small current in the armature to start with; the small current from the armature passes round the field magnets, strengthens their magnetism slightly, and consequently increases the current; this increased current further increases the magnetism, and so on, until after the first fifty or hundred turns the current and the magnetism have worked up to their full power.

Modern Generators.—In the modern D.C. dynamo the Gramme ring is entirely replaced by the drum-wound armature. This winding is quicker and cheaper to build; and a drum-wound

machine has the advantage of giving a greater output than a ring-wound machine of the same weight, owing to the fact that it has no inactive wires inside the core of the armature.

In the modern drum-wound machine the core consists of sheets of soft iron or steel which are pressed together and either keyed to the shaft or to a 'spider' which is keyed to the shaft. These sheets, or laminations, are punched with slots round their outer rim, the slots having grooves for the wedges, by which the coils are held in position.

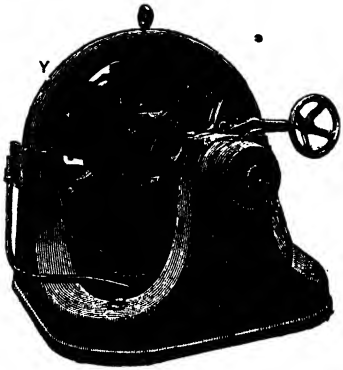


Fig. 148.—D.C. generator.

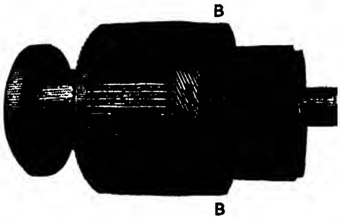


Fig. 149.—Armature.

The coils are wound separately, and after being well insulated are firmly wedged into the slots. The commutator is also built separately on a drum; the bars are insulated from one another and from the drum by mica and shellac. This drum having been previously pressed on to the shaft, the leads from the coils are soldered into grooves in the commutator-bars.

The field magnets consist of pole pieces which surround the greater part of the armature and are mounted on a continuous yoke of iron or steel usually of circular form. The exciting coils are generally placed on the pole pieces.

Figs. 148, 149 show a six-pole compound-wound D.C. generator, built by the British Westinghouse Company, and follow photographs kindly lent by the Company. The pole pieces are built of laminated steel, either cast into the yoke, Y, or bolted to it.

On each pole piece, it will be noticed, there are coils of two

different sizes. The larger is the shunt coil and the smaller the series coil. These are wound separately on suitable moulds and, having been well insulated, are firmly secured to the pole pieces.

The brushes consist of blocks of carbon pressed against the commutator by phosphor-bronze springs, and are well shown in Fig. 148. Fig. 149 represents the armature separately. Here the bars B, B can be seen connecting the armature coils with the segments of the commutator.

At the present time, dynamos and motors are seldom built with fewer than four poles, except in very small sizes. They are built up to about 80 k.w. with four poles. Above this six-pole machines are used; and for larger outputs the number of poles is still further increased, even up to twenty poles. The modern D.C. generator is as a rule compound wound and is built up to an output of 2000 k.w. or more.

Armature Winding.—Fig. 150 shows the winding of a small four-pole drum-wound dynamo or motor. The student is advised to follow the winding carefully, when it will be seen to be not so complicated as might appear at first sight. The proportion of pole pieces, slots, etc., may be taken as fairly correct for a small machine.

We have taken a simple case with 31 slots, 31 coils each consisting of one turn, and a commutator with 31 segments. A few slots, L, are drawn to show their construction, together with the wedges, W, for fixing the coils.

The coils are all numbered, those with the same numbers being really the same coil because they are connected at the back of the armature. In fact, each coil lies in two slots, one side of the coil being at the top and the other at the bottom of a slot. The span of the coil is just over one-fourth of the circumference, *i.e.* it covers eight teeth. Considering any coil, say the coil numbered 1, we see that the leads from it are brought to two nearly opposite segments of the commutator. Following the left-hand lead to the commutator, we see that another lead is connected to the same segment from the beginning of coil No. 17. Following the

other lead from coil 17, in this way we arrive at coil 2; and proceeding in this way we find that the winding is continuous and enclosed on itself.

Let the field be now excited so as to produce two North poles, N, N, and two South poles, S, S. The exciting

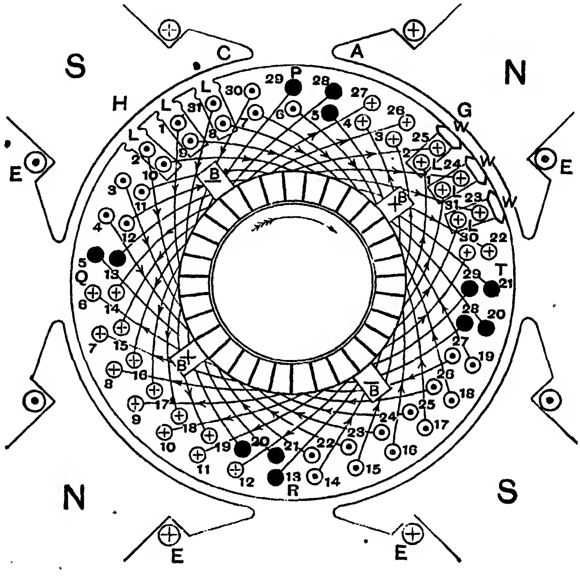


Fig. 150.—Winding of D C. generator or motor.

coils, E, E, are represented in section by the small circles on either side of the pole pieces, while the direction of the current in the various coils is represented conventionally by a point (emblematic of an arrow-head) in the circle when the current is rising up from the paper, and a "cross" (emblematic of the feathered end) when the current is sinking into the plane of the picture.

Let the armature be driven in the direction of the curved arrow, and let a resistance be connected across the brushes B, B; then, applying Fleming's rule (p. 835), we see that the current

induced in the armature coils flows downwards opposite the North poles and upwards opposite the South poles. Certain coils shown in black have no useful current flowing in them, but are short-circuited by the brushes. These coils are said to be in the 'neutral position.' As a coil passes through the neutral position the current in it has to reverse, and it would seem that the best position of the brushes is determined so that this reversal of current takes place as the coil passes between two poles. We shall see later how nearly this is so. For the present we will assume the brushes to be placed so that they are nearly opposite the pole pieces G, H.

The positive brushes, or those from which current flows, are seen to be opposite the North poles. If, keeping the polarity the same, we reverse the direction of rotation, the direction of the flow of current is obviously reversed.

Similarly, if we keep the direction of rotation the same and reverse the polarity the current is reversed.

Armature Reaction.—Taking the armature coils between A and G with the current flowing downwards in connection with those between C and H with the current flowing upwards, we see that the combination gives a North pole in the armature between A and C with its centre at P. Similarly we get a North pole at R and South poles at Q and T. The armature in fact acts as a four-pole magnet, and in operating the dynamo we are always forcing a North pole from a South pole towards a North pole, thus doing work.

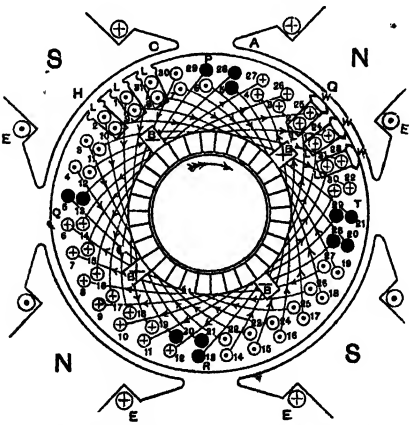


Fig. 150.—Winding of D.C. generator or motor.

But this North pole at P has the effect of weakening the backward or 'trailing' tip A of the pole G and strengthening the

forward or 'leading' tip C of the pole H, and similarly for the other poles. In the present position of the brushes this has little or no effect on the nett amount of magnetism produced in the field, but the resultant magnetism from the poles is shifted forwards, and the brushes must be shifted forwards to bring them on to the neutral position. This is called giving the brushes a lead.

The effect of this shifting of the brushes is to bring the North pole at P nearer to G than to H, so that the poles are on the whole weakened. Since the strength of the pole P varies with the load, we should theoretically have to alter the position of the brushes for every change of load. This actually had to be done with the old form of dynamo with copper brushes (see Commutation, p. 854); the use of carbon brushes in modern practice has in the main rendered this unnecessary. The brushes are moved forward as far as possible without sparking on no load; the machine then runs without sparking at all loads.

D.C. Motors.—We have so far described the dynamo as a machine which produces an electric current when driven by an engine. But it is a reversible machine; supply it with a current, its armature will revolve, and the movement may be used to drive machinery.

The dynamo is then spoken of as a *Motor*; it may be noticed that the term was used on p. 836 without explanation in speaking of Faraday's disc.

So far as the coils and working iron go, the motor is in construction similar to the dynamo, but is sometimes of different mechanical design, as in the case of tramway motors, where the yoke is extended so as to enclose the machine completely and protect it from dirt and injury.

Direct current motors are generally series or shunt wound, according to the particular work for which they are designed. Compound-wound motors are occasionally used for special work.

Before discussing series and shunt motors, however, a few words should be said on motors in general.

So far as the winding goes, Fig. 150 may be taken to represent

a motor equally as well as a dynamo. In studying the working of a motor we will use a simpler diagram (Fig. 151).

Consider a motor as above, the field being excited separately from some supply which will give a constant voltage; we have then a field of constant strength and the armature at rest within it.

Suppose a voltage denoted by E be now supplied to the armature, it will begin to move and will run up to a speed at which e (the voltage induced in it by the field), together with

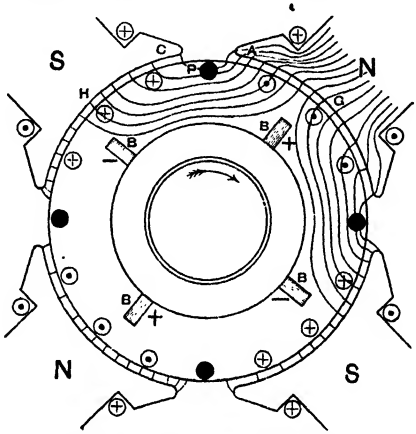


Fig. 151.—Armature reaction—motor.

the voltage drop due to the resistance of the armature, balances the voltage of supply; or, in other words,

$$E = e + ir, \qquad (a)$$

where r = resistance of armature, i = current flowing in the armature. Neglecting r, as in general the voltage drop due to it is a small fraction of E, we have $E = e$.

Now by the Law of Induction of E.M.F. (p. 835) e, the induced or counter E.M.F., varies as the product of strength of field and speed.

Hence $E \propto$ revs. per min. $\times$ strength of field. Therefore, keeping the strength of field constant, the speed varies as the supplied voltage; or, keeping the supplied voltage constant, the speed varies inversely as the strength of the field.

If the field were gradually reduced to zero the motor would run away and would probably end by flying to pieces.

A wire carrying a current exerts a force on a magnetic pole (pp. 748, 776); conversely, a magnetic pole exerts a force on a wire carrying a current.

Now it is known that the force exerted on a conductor, stationary or moving in a magnetic field, varies as the product of the current in the conductor and the intensity of the field.

Hence the twisting force or 'torque' of a motor varies as the product of the strength of the field and the total current.

A Shunt Motor answers to the conditions just described; the field is directly excited off the mains and may be taken to be of constant strength. Therefore a shunt motor when supplied with a constant voltage will run at a practically constant speed for different loads. The equation a (p. 850) shows that the effect of the resistance of the armature is to diminish the counter E.M.F. when the load increases and so to diminish the speed.

The reaction of the armature on the field, however, as in the dynamo, weakens the field, and so raises the speed, as we shall see shortly. These two effects balance to a great extent, and in a shunt motor, designed for constant speed, no difference in speed can be detected at different loads.

Hence shunt motors are used in all cases where a constant speed at different loads is desired. The speed may be readily altered by having a rheostat in series with the field and so altering the strength of the field.

Referring to Fig. 151 we see, by Fleming's rule, that if the motor revolve in a clockwise direction the current opposite the North poles N, N must flow upwards and opposite the South poles S, S downwards. It should be noticed that the brushes opposite the North poles are still positive, since the positive brush of a motor is the brush into which current is flowing. As before, the armature acts as a magnet; only in this case the poles of opposite polarity in armature and field are approaching one another. In fact, the motion of the motor may be considered

as due to this. We have two pairs of North and South poles fixed, and, by conveying current to the armature through the brushes, we create two other pairs of poles which are always attracted towards the first two pairs. As in the case of the dynamo, these poles of the armature react upon the field; only in this case they strengthen the trailing tip A and weaken the leading tip C of the pole pieces, so that for the brushes B, B to be on the neutral they have to be given a backward lead. In this position the armature has the effect of demagnetising the

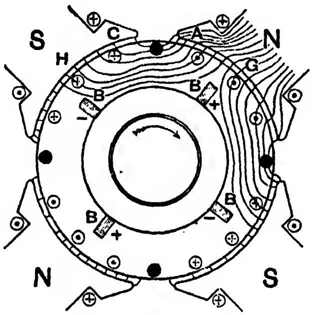


Fig. 151.—Armature reaction—motor.

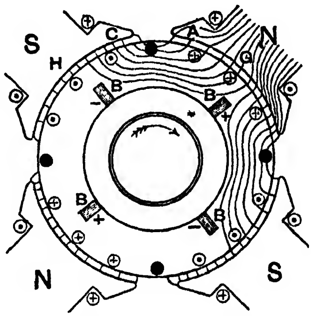


Fig. 152.—Armature reaction—dynamo.

field to a certain extent. The effect of these reactions is shown by the distortion of the lines of force (Fig. 151). A similar diagram (152) is given for a dynamo.

In the motor, as above, if we reverse the current in the field or the armature, the armature will run in the reverse direction; but if we reverse both it will run in the same direction. Hence to reverse a motor, whether series or shunt, we must reverse the field relative to the armature.

A Series Motor cannot be considered in quite the same way, for the strength of the field changes with every change of load. Consider a series motor to the armature of which a brake is applied, adjusted so that the motor when it is running will exert against it a torque, T. If an E.M.F., E, is supplied to the motor, it will run up to such a speed that the counter E.M.F., e, induced in the armature by the field, together with the voltage-drop due

to the resistance, R_a of the armature, and R_f of the field, balance the impressed E.M.F., E.

That is, $$E = e + (R_a + R_f)i, \qquad (\beta)$$

where i is the current flowing in the field and armature.

Again, $T \propto i \times$ strength of field. Now the strength of the field up to a certain point varies directly as i, and if this is the case $T \propto i^2$.

Also e, the counter E.M.F., varies as the product of the strength of the field and the speed.

That is, $$e \propto i \times \text{speed}.$$

Hence, $$i \times \text{speed} \propto E - (R_a + R_f)i.$$

At small loads we can neglect $(R_a + R_f)i$ compared with E, so that, when E is constant, i varies inversely as the speed. For all loads the torque continually diminishes as the speed increases, and the torque is a maximum at starting.

These features of the series motor make it specially adapted for traction work, crane work, and for all work where a big torque at starting and a variable speed are required.

Compound wound motors are used if a large starting torque combined with a fairly constant speed is required.

Neither in the case of shunt nor series motors would it be safe to switch on the full voltage at once. So in starting a shunt motor the field current is first switched on and the armature is switched on with a resistance in series with it. This resistance is gradually reduced so as to raise the voltage supplied to the armature and is finally short-circuited.

In the case of the series motor, a resistance is connected in series with the motor at starting and gradually reduced, so as to raise the E.M.F. to full voltage.

Commutation.—The problem of commutation is a somewhat complicated one, but its main points may be briefly considered.

As a coil of a machine passes a brush it is short-circuited for a brief interval of time; during this time the current in the coil has to die down to zero and then begin again in a reverse

direction. Owing to the self-induction of the coil, the change of this current has the effect of generating an E.M.F. of a few volts in the coil, which E.M.F., by Lenz's Law, opposes the change of current in the coil. Were this E.M.F. not neutralised the current would perhaps not reverse in time, but would flow across the commutator to the brush in the form of sparks, burning away the brushes and damaging the commutator. When possible, this E.M.F. is neutralised by shifting the brushes forward in a dynamo and backward in a motor, so as to bring the short-circuited coil into a field which opposes the E.M.F. and helps the current to reverse. This means a still further increase in the 'lead,' which has been referred to above (Armature Reaction, p. 848), and still further demagnetisation of the field. In some motors, such as tramway motors, this lead cannot be given, since the motor has to be reversed, and in such a case careful design and the use of special brushes is all that can be relied on to mitigate the sparking.

With very high speed machines, such as turbo-generators and motors for high-speed pumps, or for great variation in speed, it is necessary to provide auxiliary poles. These poles lie between the main poles, and have a winding which provides the necessary commutating E.M.F.

For good commutation, it is necessary that the self-induction of the short-circuited coil should be small compared with its resistance, for which reason carbon brushes are now always used instead of copper brushes, with the object of inserting a resistance in the path of short-circuit.

Alternators.—Going back to the Gramme ring (Figs. 145, 146), suppose we replace the segmented commutator C, against which the brushes BB press, by a pair of collector rings connected to the ends of two particular coils at opposite ends of a diameter of the Gramme ring. Each brush, then, instead of receiving its current always from the highest, or always from the lowest point of the ring, receives it from a point which is continually changing in position; hence, at one instant during a revolution it is receiving and passing on the external circuit a

positive current, half a turn later it receives a negative current, while at the quarter and three-quarter turn it receives no current at all. Thus we have an alternating current giving one complete wave—backward and forward—for each revolution of the armature.

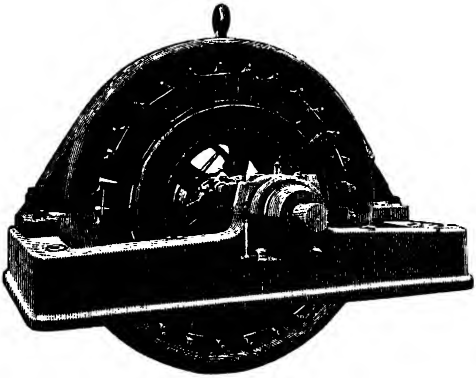


Fig. 153.—Alternator.

Fig. 154.—Armature.

Figs. 153, 154 represent a four-wire, two-phase stationary field alternator and its armature.

The collector consists of four rings of brass, well insulated from one another, and separated by projecting rings of insulating material. The collector rings are seen in Fig. 154, and the brushes taking the current from them in Fig. 153.

As we have seen on p. 774, it is an economy to use a high voltage when transmitting power to a great distance. For this reason, alternators or machines generating an alternating current are largely used in big power schemes, it being possible to transform the voltage up and down by means of static transformers. A further reason for their use is that alternators and A.C. motors are simpler and more capable of standing overloads than D.C. machines, since the commutators and commutation troubles are done away with.

At the present time (1907) alternators are nearly always built with a revolving field and a stationary armature, the current being conveyed to the field by brushes and collector

rings. If the machine were built with a revolving armature, the collector gear would become complicated, especially in high-tension-work; and the armature being exposed to centrifugal stress, the insulation would be liable to break down.

Fig. 155 represents a three-phase revolving field alternator; the collector and brushes are seen to be of simple construction.

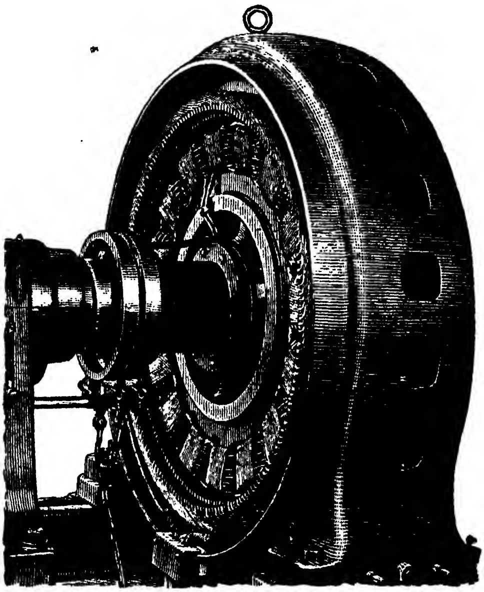


Fig. 155.—Revolving field alternator.

The field-coils are held by the pole-tips, which are keyed to the poles. The three-phase leads are brought to a terminal box seen at the bottom of the picture.

The efficiency of a motor or dynamo is best determined by measuring the various losses in the machine. The losses are due to (1) Resistance in field, armature, and brushes; (2) Hysteresis in the iron; (3) Eddy currents; (4) Friction and windage.

The first of these is determined by measuring the resistance

of the armature and field, and the three last of them by running the machine light. We have then

$$\text{Efficiency} = \frac{\text{output}}{\text{input}} = \frac{\text{output}}{\text{output} + \text{losses}}.$$

Polyphase Working.—Now, referring back to our rudimentary dynamo, the magneto-machine shown in Fig. 139, suppose that a second pair of coils, C′ and D′ (not shown in the figure), be mounted on the spindle by means of a bar at right angles to that which carries C and D; and these coils be connected up to a second pair of collecting rings A′B′ upon the spindle, there will evidently be produced in the new coils, and

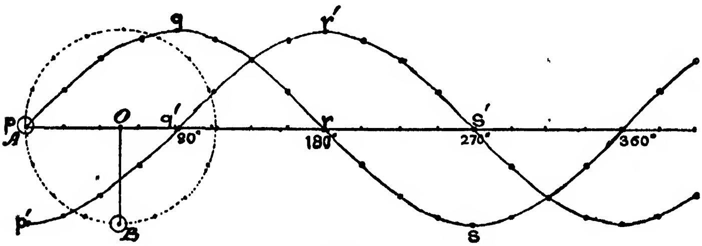


Fig. 156.—Two-phase alternating current.

transmitted to the new collectors, an alternating current identical with that produced in CD, except that when the CD current is greatest, the C′D′ current is least, and *vice versâ*. If the CD current be represented by the wave *pqrs* (Fig. 156), the C′D′ current is represented by the wave *p′q′r′s′*, which is the same wave shifted forward a quarter of a wave length; that is, the two waves are identical in *form*, but differ in *phase* by a quarter period. This is described as '90°' difference of phase, for each wave is constructed by means of a complete revolution of a vector. The wave *pqrs* has, at each point, an ordinate (*i.e.* a perpendicular height) equal to that of the corresponding position of the vector OA, rotating clockwise, while the wave *p′q′r′s′* has those of the rotating vector OB (which follows 90° behind OA). Obviously, with two pairs of coils supplying current, twice as much work as before has to be done in turning the handle.

In the same way, if we have three pairs of coils, CD, C′D′, C″D″ (Fig. 157), carried by three bars mounted on the spindle and making 120° with each other, we shall obtain from the three pairs of collectors, three current waves identical in form, but differing in phase by one-third of a period, or 120° (Fig. 158). To produce these three currents a triple amount of work must be done in driving the machine.

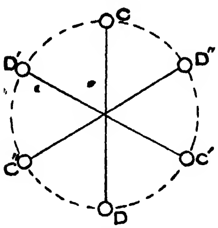


Fig. 157.—Arrangement of three pairs of coils.

Reverting to the Gramme machine, if we have two pairs of field-magnet coils with poles (arranged as in Fig. 159), there will be two complete waves (four reversals) of the alternating current for each revolution of the armature.

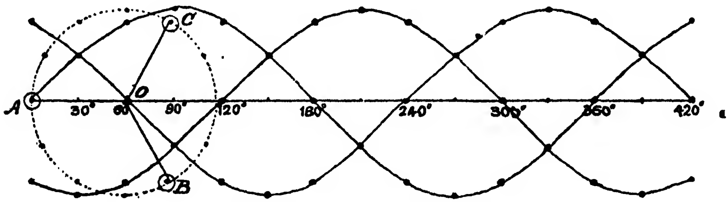


Fig. 158.—Three-phase alternating current.

It is now possible by concentrating the coils (suitably connected up) into groups, as shown opposite to N, S, N, S in Fig. 159, to leave space on the armature core at H, K, L, M, upon which a second set of coils may be wound; these, connected up to another pair of collectors, give another alternating current differing in phase by a quarter period.

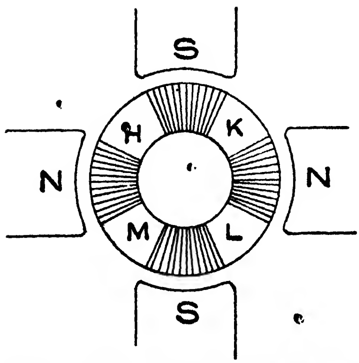


Fig. 159.—Gramme machine with two pairs of field magnets.

This is known as a two-phase dynamo, and similarly,

by using three sets of coils, we have a three-phase dynamo; nearly all polyphase dynamos are two- or three-phase.

There is great variety in the construction of alternators, according to the purpose for which they are designed, whether for high or slow speed or for high or low frequency. Frequencies in common use are from 25 to 50 cycles per second.

We may notice that the economy in the use of polyphase currents arises from a saving of copper and a reduction in the loss of energy in the mains, and from economy in the dynamo itself.

Thus, if we have three groups of 100 incandescent lamps, each group using one of the three currents of Fig. 158, differing in phase by 120°, we may use a common return wire—and this wire will actually have to carry no current if all the lamps be in use, for these three waves neutralise each other, whereas, if the three currents were all in the same phase, the return wire must be capable of carrying three times as much current. If two groups be in use and the third cut off, the current from these two waves combined (owing to their difference of phase) is equivalent to that of one group only; so that a return wire fit for one group is all that need be supplied.

A three-phase dynamo or motor will give about 50 per cent more output than a single-phase machine of the same size and speed.

Polyphase Motors.—The polyphase induction motor is a machine of great practical utility. As an illustration we give a short and simple description of a two-phase motor, *i.e.* a motor driven by a *pair* of alternating currents. These currents, being derived from a single dynamo, are represented by waves identical in form, but differing in phase by a quarter period (90°). Four wires are required for supplying the currents, viz. a lead and a return wire for each current.

The stationary part or 'stator' consists of a ring built of thin iron plates, with teeth projecting on their inner circumference. The coils lie in the slots thus formed, and are connected in groups. We will consider a two-pole motor, *i.e.* one with two groups per

phase. For the sake of clearness, four pole pieces (A, B, C, D, Fig. 160) are shown. Round A and C are wound coils connected in series to the first phase leads, and round B and D are coils connected in series to the second phase leads; only two turns are shown in each coil. At the instant when the first phase current is at its maximum, and flowing as represented by the arrows, the lower face of A is a N. pole, and the upper face of C a S. pole; at this instant the second phase current is nil. The lines of magnetic induction, or flux, are therefore arranged as in Fig. 160.

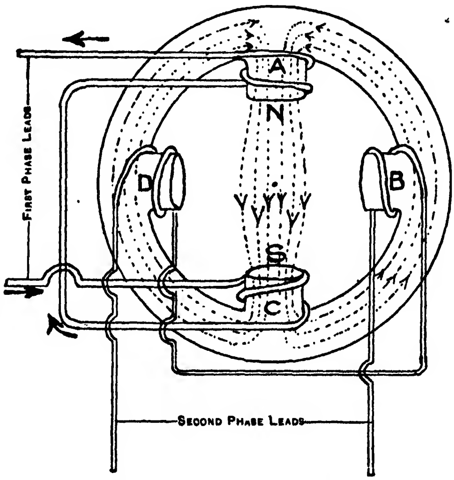


Fig. 160.—Two-phase induction motor (armature removed).

Fig. 161, I represents the same facts as Fig. 160; in it the general direction of magnetic flux is shown by the big arrow-head: the coils are represented, in section, as before, p. 847. The plain circles indicate coils in which no current is flowing.

At one quarter of a period later the first current has dropped to nil, while the second has risen to a maximum; and the magnetic flux is as in Fig. 161, II.

At the half period the first current has risen to a maximum in the reversed direction, the second current is nil, and the flux as in Fig. 161, III.

At three-quarters of a period from the start the first current is nil, the second is at a maximum in the reversed direction, and the flux as in Fig. 161, IV.

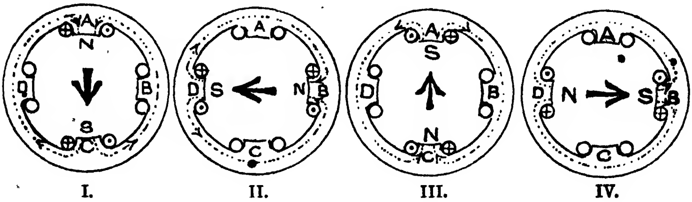


Fig. 161.—Rotating magnetic field.

And after a full wave or complete period we revert to the condition of Fig. 161, I.

Consideration of these figures shows that the effect of the two-phase alternating currents upon the stator coils is to produce a magnetic field of practically constant strength, whose direction is continually rotating, in lieu of a stationary field such as we have, *e.g.* in the Gramme machine of Figs. 144, 145.

Now place within the field an armature consisting of an iron ring, on which are wound several coils, each short-circuited, and imagine the armature clamped firmly in any position; the field due to the stator coils is immediately distorted, so that practically all the lines of force run through the iron of the armature as in Fig. 162. Then, as the field rotates, the points at which the lines of force enter and leave the armature ring also rotate simultaneously; hence lines of force are continually being threaded in and out of the short-circuited armature coils, and in consequence, powerful currents are induced in the coils.

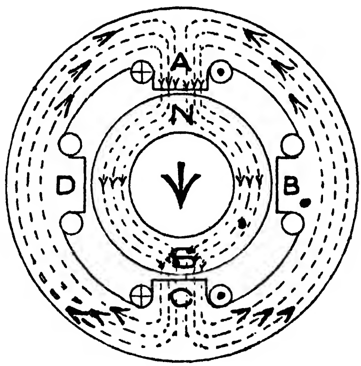


Fig. 162.—Direction of flux in two-phase induction motor (armature in).

Lenz's Law (p. 763) "that the direction of an induced current is such as to resist the movement which produces it" has as a corollary *that the force exerted in a field is such as to cause movement which will reduce induced currents.*

Hence the armature is acted upon by forces tending to move it in such a way as to reduce the induced currents; hence, if the axle of the armature be unclamped, it will begin to move in such a way that the coils may no longer cut through any lines of force, and this occurs if the armature rotates in the same direction as the magnetic field and keeps pace with it exactly. Therefore, if the motor be 'running light,' with no load whatever (and no friction in the bearings or elsewhere), it will spin at exactly the same pace as the magnetic field—it will make 100 revolutions per second if the exciting currents alternate 100 times (200 reversals) per second. In this condition no currents are induced in the coils.

Now give the motor work to do; the load coming upon it will check the speed of the armature, or 'rotor,' as it will hereafter be called, so that it will revolve more slowly than the rotating field; lines of force will again be cut by the wires of the short-circuited coils, and currents will again be induced in them (though, unless the load be so heavy as to pull up the motor to a dead-stop, these currents will not be so intense as when the axle was clamped). As described above, forces act on the 'rotor' (in accordance with Lenz's Law) tending to reduce the production of currents by avoiding the cutting of lines of force. The forces cause a torque on the axle, urging it round in the direction of the rotating magnetic field, until a speed is reached when the number of lines cut by the rotor coils, and the currents induced in them, are such that this torque exactly balances the load. In practice the speed of the rotor at full load is 5 or 6 per cent lower than that of the field.

This percentage of slip is proportional to the resistance of the rotor. Since a rotor of high resistance means a considerable loss of power, and a reduction in efficiency, it is desirable to keep the slip-percentage low.

The starting torque of the motor is, however, proportional to the resistance of the rotor, so that if we want a big torque at starting the rotor should have a comparatively high resistance.

In practice, a compromise has to be made between these two demands, and with a slip at normal load of about 5 or 6 per cent on moderate-sized motors we can get at starting about twice full load torque with full voltage.

Induction motors of small size, say up to 5 H.P., are generally switched straight on to the line at starting. For motors of large size this would mean drawing a very heavy current from the line at the time of starting, and so a transformer is used to reduce the voltage.

For very big motors, or when it is not desirable to draw a very heavy current from the line, or for motors used for haulage work, etc., the rotor is wound with a three-phase winding, and by means of collector rings and brushes a resistance is inserted at starting. This resistance is divided into steps, which are cut out or short-circuited as the motor runs up to full speed.

Figs. 163, 164 represent respectively the stator and rotor of a 10-H.P., three-phase (type C.B.) motor.

In the stator the coils seen are machine wound, and consist of several turns of wire, the number depending on the voltage speed and frequency.

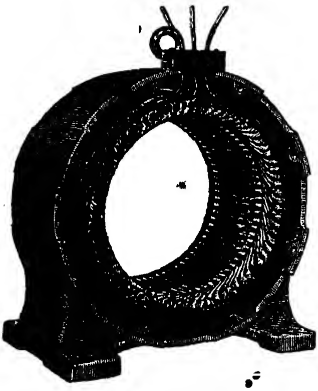


Fig. 163.—Stator.

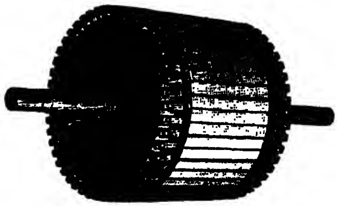


Fig. 164.—Rotor.

Type C.B. Induction Motor.

They are separately insulated, wedged into slots in the laminated iron, and connected up to form poles. In the machine illustrated there are eight poles instead of the two described above.

The rotor winding consists of copper bars, well insulated, slipped into the slots in the core, and then bolted to the short-circuiting rings. The core is built up of sheets of soft iron or steel which are pressed together. These sheets or laminations are punched with slots round their outer rim.

Figs. 163, 164, as well as Figs. 153, 154, 155 above, are engraved from photographs kindly lent by the British Westinghouse Electric and Manufacturing Company.

The Single Phase Series Motor.—We have seen above that if we reverse the current in both field and armature of a series motor, the rotor will run in the same direction. Suppose then we supply an alternating E.M.F. to the terminals of a series motor, since the current in the armature and field are always reversed together, the torque will be always in the same direction, and on this principle it has been found possible to build satisfactory motors.

To reverse the motor it is necessary to reverse the field relative to the armature.

The advantage of the single phase series motor for railway work is that, as an alternating current is used, static transformers can be employed in the sub-stations, thus doing away with revolving machinery which requires attention.

For such a system the current is fed to an overhead wire at a voltage of from 3000 to 15,000 volts, according to the length of the line, and having been collected at this voltage is transformed down by means of static transformers on the cars to a working voltage of, say, 250. The rails are used as the return circuit. Current of a comparatively low frequency, say 25 cycles per second, must be used for the single phase series motor.

Rotary converters are machines for converting alternating to direct currents, and are much used in big power schemes. In its normal form, the rotary converter is practically the same as a shunt or compound wound D.C. generator, but in addition to the com-

mutator we have a collector on the other end of the shaft, which is connected up to the armature as in an alternator with a stationary field. The alternating current is fed through the collector rings and the direct current is collected from the commutator.

In the London Underground Electric Railways, the three-phase current from the turbo-generators in the power-house at Chelsea is fed at 11,000 volts to various sub-stations along the line. It is there transformed down by static transformers and converted to a 600 volt direct current by 1500 k.w., 1200 k.w., and 800 k.w. rotaries and fed at this voltage to the rails.

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THE END

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